A NEW PROTOCOL FOR EVALUATING CONCRETE CURING EFFECTIVENESS

A Thesis
by
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ABSTRACT

Excessive early-age concrete surface moisture evaporation causes many problems of concrete pavements, such as plastic shrinkage cracking and delamination; the use of liquid membrane-forming curing compounds is one of the most prevalent methods to mitigate the issues. However, the present standard test, ASTM C 156-98, “Standard Test Method of Water Retention by Concrete Curing Materials” has some inherent limitations in assessing the curing effectiveness of concrete. To better apply curing practices and qualify the curing compound, a new evaluation protocol is introduced in this study.

The new protocol consists of using measured relative humidity and temperature to calculate an effectiveness index (EI) which serves as an indicator of the effectiveness of curing. Moistures loss and surface abrasion resistance measurements were made on concrete specimen, and were found to have significant correlation with EI, where higher EI were associated with lower moisture loss and higher surface abrasion resistance. EI was also found to be sensitive to ambient wind condition, types of curing compound and the application rate of the curing compound. Dielectric constant (DC) measurements were also made on concrete specimens indicating the free moisture content on the surface concrete. The DC measurements were also found to differentiate the quality of curing under different ambient conditions, with various types of the curing compounds and the w/c of the concrete mixture. The utility of using the new protocol to assess concrete curing compound effectiveness was also evaluated under the field condition. Both EI and DC measurements showed potentials to distinguish the curing quality for concrete pavement construction.

DEDICATION

To my parents for their unconditional love and continuous support throughout my life and LFC who inspired me to never give up

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1. INTRODUCTION

The large surface-area-to-volume ratio of a concrete pavement, as a major difference compared to most other concrete structures, makes concrete paving highly susceptible to moisture loss through evaporation. Under the influence of certain field conditions including a variety of combinations of temperature, solar radiation and wind, excessive early-age water evaporation could occur at the surface of a concrete pavement during construction. These climatic effects may lead to insufficient surface concrete hydration and increase the surface porosity of concrete to a level such that the strength and the durability of concrete would be impaired, which could induce even detrimental impacts, such as plastic shrinkage cracking and delamination (cause of spalling) that will eventually affect the long life of a concrete pavement [1, 2].

To moderate the unexpected early-age moisture loss, applications of a variety of curing technologies on the surface of concrete pavement have been widely used to address evaporation. Among the several methods of curing, liquid membrane-forming curing compounds are the most widely used to cure concrete pavements [3]. It has been well recognized that proper curing is the key to success of pavement performance and the quality of curing compound should be related to the curing performance [1-5]. Therefore, a technology for evaluating the effectiveness of the curing compound is indispensable.

However, a method for assessing the curing effectiveness under field conditions is mostly non-existent; though the American Association of State Highway and Transportation Officials T 155 (AASHTO T 155 1997) and the American Society of Testing and Materials (ASTM C 156) describe a laboratory procedure to characterize the water retention capability of a curing compound, inherent limitations are prevalent.

Therefore, a new protocol for evaluating concrete curing effectiveness is proposed in the present study. Besides the moisture retention test as described by the ASTM standard test, the new protocol also consists of the determination of the Effectiveness Index (EI) and making dielectric constant (DC) measurements at the concrete surface to qualify curing practice. EI is calculated based the concrete maturity concept using concrete surface relative humidity and temperature data measured by a device especially designed for this purpose. The DC of a concrete surface measured by a Percometer is used to indicate the free moisture content on the surface of concrete which is considered to be affected by the curing practice. The objectives of this study consider the followings:

- Determine the Effectiveness Index (EI), surface abrasion weight loss and moisture loss for concrete specimens and identify the correlations between them.
- Perform sensitivity analysis for EI to various types of curing compounds at different amounts of application rate, under no wind or wind condition.
- Conduct dielectric constant (DC) measurements for concrete surface and perform sensitivity analysis for DC to various curing treatments at different levels.
- Validate the utility of EI and DC measurements through field research investigations.

This thesis is organized into five chapters; first, Chapter 2 provides an extensive literature review of concrete curing as background information and provides theoretical bases for the investigation. Chapter 3 introduces a laboratory investigation approach and describes the laboratory data collection process taken in this project. Chapter 4 focuses on the obtained laboratory results and presents the analysis of them. Chapter 5 summarizes the research findings of applying the new protocol on freshly placed concrete pavements during a field investigation in Victoria, TX and validates the utility of the proposed new protocol under field condition. Section 6 gives the general conclusion of the research findings and provides recommendations for future investigations.

2. LITERATURE REVIEW

This chapter provides an extensive literature review on various topics that are related to knowledge of concrete curing practices and prepares some theoretical basis involved in this study. Specifically, the background information on the curing of concrete, the method of using liquid membrane-forming compounds for curing concrete and some technologies for evaluating the concrete curing effectiveness are reviewed. Also, the theoretical basis of the dielectric property of concrete is established for the potential of using measured dielectric constant of concrete to assess the effectiveness of curing compounds, which is one of significant constitutes of the proposed protocol.

2.1 Background of Concrete Curing Practice

In this section, the hydration process of concrete is explained to provide a basic understanding of the need for better curing practices. Also, the distresses of concrete pavements associated with insufficient concrete curing practice are presented, and some of the widely used methods for concrete curing are reviewed.

2.1.1 Concrete Hydration Process

Understanding the hydration process of concrete is a preliminary for introducing the need for concrete curing. The hydration of concrete is a result of a series of chemical and physical processes which come from the reaction between cement and water [1, 6]. While the hydration process continues, the strength of the internal bonding between hydrated cement particles will increase and the porosity between the particles will decrease [4].

A scanning electron microscope (SEM) is used to observe the microstructural development of concrete hydration products. Figure 2-1 shows the microstructures of partially hydrated and un-hydrated cement particles under the SEM.

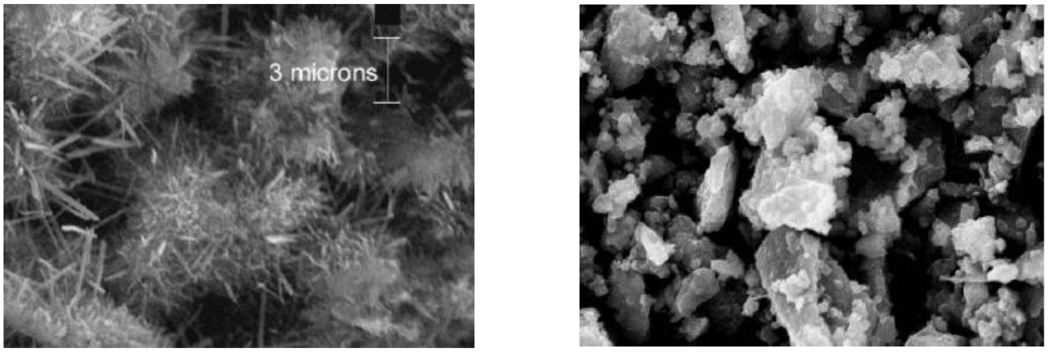

Figure 2-1 Graphs of partially hydrated (left) & un-hydrated cement particles [4]

As shown in Figure 2-1, in contrast to the un-hydrated cement particles, the surfaces of the partially hydrated cement particles are densely covered with randomly oriented hydration products. During the process of concrete hydration, the presence of water ensures the chemical reactions and the formation of these products [7, 8]. These hydration products play significant roles in the strength development of concrete during the hydration process, and also have substantial influence on the life-long performance of concrete. It was indicated that calcium silicate hydrate, one of the most important hydration products of concrete, contribute the most to strength development of cement based materials [1]. Without creating enough of these hydration products into the spaces between cement particles during the hydration process, strength issues might occur since the degree to which the spaces between cement particles have been filled with hydration products is the key to strength development of concrete [7, 8].

Ensuring the high rate of hydration is the key to success of cement hydration development because fewer amounts of hydration products are created within a certain period of time if the hydration rate is low. Researchers found that the rate of cement hydration would drop to a low level when cement paste is exposed to an environment of low relative humidity (RH); it was indicated that the rate of hydration of cement paste under an environment of 80% RH is only 10% compared to that of cement paste under an environment of 100% RH [9]. Clearly, the availability of desirable amount of moisture in a cement paste is very significant to ensure a desired rate of cement hydration and achieve better performance of concrete pavement.

Two types of water are found in hardening concrete [1]. The first type is non-evaporable water, named as gel water, which is the water physically combined into the interlayer spaces of the hydration products during the hydration process; the other type is evaporable water, also known as capillary water, which is defined as the water available to be consumed during the chemical reactions of forming hydration products [1]. However, due to the fact that concrete pavements usually have a large surface-area-to-volume ratio, the surface of concrete is easily exposed to ambient environment conditions with high evaporation potential, such as high temperature and strong wind conditions, which cause excessive moisture loss at the surface of concrete pavements at early ages. Because of the irreplaceable role of water in the cement hydration process, losing them at the surface of concrete could lead to detrimental consequences in terms of both the strength and durability of concrete pavements. Therefore, in order to have sufficient amount of moisture to sustain the cement hydration process to achieve desired concrete performance, it is very necessary to apply curing practices to moderate the moisture evaporation at the surface of concrete [4].

2.1.2 The Need for Better Curing Practices

Many problems are associated with concrete pavements with inadequate curing practices. Typically, the most common curing-related distress of concrete pavements is plastic shrinkage cracking (PSC) [10]. Fresh concrete exposed to hot, windy and arid environment are most easily to show such kind of distress at the surface area. Particularly, when the moisture evaporation rate at the top surface of concrete exceeds the rate at which the moisture is supplied through the concrete bleeding process (the process where excessive mixing water are forced to go upward due to the settlement of aggregate and cement particles) , PSC is easily formed from the failure to resist the stresses induced by the volumetric contraction of concrete due to moisture loss before enough tensile strength has been developed [11]. PSC are usually in the form of parallel and well-spaced cracks at the surface of concrete; however, they could penetrate into the concrete slab deeply due to aggravation. Another form of PSC could be in random appearance of 15 – 30 millimeters deep map cracks; these small cracks are not noticeable at the beginning, but would make it possible for freezing-thawing damage and deicing salts related deterioration to take place by providing entries [10, 11].

Figure 2-2 Typical forms of plastic shrinkage cracking

Another common concrete pavement distress associated with insufficient curing is concrete surface delamination. Generally, the delamination usually occurs on the shallow surface of concrete is mainly due to that the moisture gradient induced horizontal stresses exceed the shear strength of concrete [12]. As shown in Figure 2-3, the surface of concrete is exposed to ambient environment and the moisture at the surface is easier to evaporate than the interior moisture of the concrete pavement, therefore a moisture gradient is developed in the vertical direction of the concrete and the degree of the gradient is affected by the ambient evaporation condition and the quality of the applied curing practice after concrete is placed. In some cases, if the moisture evaporation rate is large enough and the quality of curing is not sufficient to moderate the evaporation of the surface moisture, the excessive moisture loss would lead to a non-uniform gradient of relative humidity (RH) through a concrete slab’s depth as shown in Figure 2-3. The stress induced by the non-uniform RH gradient would create a horizontal failure plane at the shallow surface of a concrete pavement, and result in the weakening of the concrete surface resistance to horizontal stresses [13]. When the horizontal stresses surpass the shear strength of concrete, the surface delamination is developed.

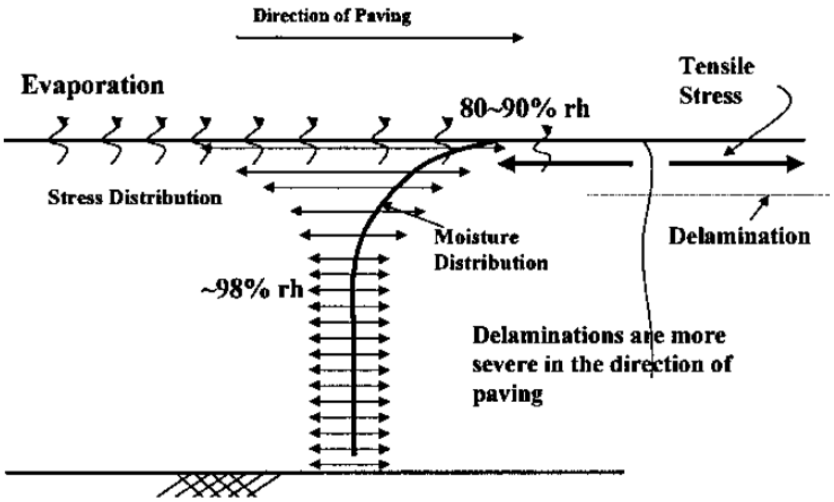

Figure 2-3 Formation of horizontal delamination [12]

Research funded by TxDOT indicated that concrete surface delamination could directly induce even more severe issue, i.e., spalling, which is described as the dislodging or breakdown of concrete sections along either transverse/longitudinal joints or cracks in a concrete slab within a distance of 2ft of the joint or crack [12, 14], as shown in Figure 2-4. It was also suggested that significant spalling was not likely to occur unless delamination had been formed; excessive traffic loading, accumulated incompressible materials within joints of pavements and freezing-thawing cycles could lead to extension of this type of distress [12, 15, 16]. The spalling issue of concrete pavements has negative influence on the riding quality and the repair of such distress is troublesome.

Figure 2-4 Spalling (left) and horizontal delamination [12, 15]

As mentioned in the section, excessive early-age concrete surface moisture loss is one of the fundamental reasons that may cause different types of distresses of concrete pavement. Therefore, the study of how to effectively moderate the undesired excessive moisture loss is one of the major subjects in the research of concrete pavement performance.

2.1.3 Methods for Curing Concrete

The purpose of concrete curing is to maintain satisfactory conditions, i.e., proper moisture content and temperature, such that desired concrete properties are developed [4]. According to the guide for curing concrete reported by ACI Committee 308, concrete curing approaches consist of two phases; the first phase is initial curing of concrete, which is defined as the curing practices implemented during the time interval between the placement of concrete and the final surface finishing of concrete; the second phase is final curing, referring to the curing measures implemented after the final surface finishing of concrete [4, 10].

The major objectives for initial curing are to control the evaporation of the concrete surface bleeding water and prevent further evaporation of capillary water inside surface concrete to avoid even worse consequences, though the loss of bleeding water has no detrimental effects [17]. Two methods are available to achieve initial curing, fogging and the use of liquid-applied evaporation reducers [4]. The fogging method is conducted by using a specially designed nozzle to atomize water into mists, which is very helpful in protecting concrete from surface drying [4]. Liquid-applied evaporation reducers are considered valuable to provide protection against excessive evaporation of bleeding water, but lack of test methods, guidance and specifications impede the wide application of using them [17].

In a narrow sense, the curing methods that people generally refer to are final curing methods. These methods are divided into two categories: water-added methods and water-retentive methods [4]. Water-added methods consist of sprinkling, ponding or immersion, burlap, sand curing and so on; water-retentive methods include plastic sheets method and the application of liquid membrane-forming curing compounds [18].

Among the water-added methods, sprinkling method is excellent in providing curing protections, but the high cost of water in water shortage areas and the limitation to non-freezing condition are disadvantages that impede the application; ponding or immersion is the most thorough water curing method, but it is seldom used because of the cost for labor and time; methods that use materials to hold moisture like burlap are frequently applied to cover the surface of concrete pavements, but once the materials dry out, periodic moistening is still needed to prevent the material from drawing moisture from the surface of concrete [4]. Among the water-retentive methods, placing plastic sheets method is time-consuming for large concrete pavement areas, so it is practical for only small areas and the use of this method is limited by the wind condition; the method of using liquid membrane-forming curing compounds is considered as the only economical method for curing concrete pavements which have a large surface-area-to-volume ratio, and the features of easy-application and free-maintenance make it the most widely used approach for curing concrete pavements in the United States [17, 19].

Figure 2-5 Application of curing compound on concrete pavement [3, 20]

2.2 The Use of Liquid Membrane-forming Compounds for Curing Concrete

This section mainly focuses on introducing the liquid membrane-forming curing compounds method for its significance in the practice of curing concrete. The characterization of curing compounds, factors that affect concrete curing and methods for assessing concrete curing effectiveness are introduced in this section.

2.2.1 Curing Compounds Characterization

Curing compound is usually in the form of liquid, and once has been properly applied, it would serve as a layer of coating at the surface of new-paved concrete pavements to slow down the evaporation of concrete surface moisture and reflect heat if the compound is pigmented. The application of curing compounds would create a favorable moisture and temperature environment for the concrete hydration process [21]. Specifications for curing compounds are covered by ASTM C 309 [22] and ASTM C 1315 [23]. In ASTM C 309, the types of curing compounds are classified based on colors: Type 1 – Clear without dye, Type 1-D – Clear with fugitive dye and Type 2 – white pigmented; and are also categorized by the solids dissolved in the compounds: Class A – No restrictions and Class B – Must be a resin-based composition [22].

ASTM C 309 [22] and ASTM C 1315 [23] also provide some basic criteria for selecting curing compounds based on the following properties: water retention capability, reflectance properties, drying time requirements and some other general requirements.

Water retention capability is addressed in both ASTM C 309 and ASTM C 1315 and is the major criterion for evaluating the performance of curing compounds. It is usually determined by the amount of the cumulative moisture loss of a concrete specimen sprayed with the tested curing compound after a fixed period of exposure to a controlled laboratory environment and the test is followed by ASTM C 156 [24]. ASTM C 309 specifies a maximum moisture loss limit of 0.55 kg/m^2 for specimens applied with curing compounds at a fixed rate of application, and ASTM C 1315 restricts the maximum moisture loss to no more than 0.4 kg/m^2 within 72 hours. However, it is indicated that the test results for moisture loss are highly variable, especially the precision of this method is poor between different laboratories, which results in strong debates between buyers and sellers regarding whether this method is appropriate to evaluate the effectiveness of curing compounds [10, 18]. Further discussion of the use of ASTM C 156 will be included in Section 2.3 – Curing compound effectiveness evaluation approaches.

Reflectance property of curing compounds is also described in both ASTM C 309 and ASTM C 1315, and is only valid for white pigmented compounds [23]. It refers to the ability of curing compounds to reflect solar radiation which helps with temperature control for concrete hydration and reduces early-age concrete surface stresses due to drying shrinkage [18]. It was also suggested that white pigment could serve as an indicator for quantifying the uniformity of the curing compound application [10]. ASTM C 309 stipulates that the daylight reflectance should not less than 60% [22].

Drying time is another important property of curing compounds. In order to ensure the workability for workers to perform joint sawing tasks on the surface of concrete after curing compounds are sprayed, and considering that curing compounds are very susceptible to be washed away by rainwater if it would rain, ASTM C 309 and ASTM C 1315 specify the drying time should be no more than 4 hours [22, 23]. Some state DOTs prescribe shorter drying times to account for fast drying conditions; an empirical equation was also developed to predict the drying time for curing compounds under different environment conditions [10].

Some other requirements are also mentioned in ASTM C 1315 in addition to the three criteria listed in both ASTM C 309 and ASTM C 1315, such as ultraviolet light (UV) degradation-yellowing, acid and alkali resistance and adhesion requirement [23]. Ultraviolet light (UV) degradation-yellowing requires that curing compounds should be durable and free of peeling and blisters issues at the surface of concrete; the acid and alkali resistance should be tested based on the described procedure in the standard for 48 hours without showing disintegration, blister and pin-hole. In order to evaluate the bonding effectiveness of the adhesives in curing compounds, adhesion is also tested in accordance with the procedure illustrated in the standard [23]. For some other requirements that go beyond the specifications as described in ASTM standards, users should negotiate with the curing compound supplier for further instructions [22].

2.2.2 Factors Affecting Curing Quality

Once the type of curing compound is chosen for a specific project, the determination of time of application, rate of application and the uniformity of application of the curing compound are the most significant factors that will affect the success of the concrete curing process [5, 25, 26].

2.2.2.1 Time of application

The time for applying curing compound is very important because curing compounds may not be effective if they are sprayed too late to prevent excessive amount of concrete surface moisture from evaporating; while early application could lead to the degradation of the curing quality when the curing compounds are mixed with concrete surface bleeding water [4]. The determination of the time to apply curing compounds has always been an issue with many disputes.

Many standard and manufacturer's guidances indicate that curing compounds should be applied when concrete surface bleeding sheen has disappeared [17]. ACI 308 states that the optimum time for applying curing compounds is when the evaporation rate of the cumulative bleeding water exceeds the bleeding rate [4]. However, the determination of this optimum time is not easy during the constructions of concrete pavements, especially for the projects in which a low water-to-cementitious material ratio and fly ash are used, the surface bleeding sheen is almost negligible, which makes it hard to decide whether the evaporation rate has exceeded the bleeding rate [5]. According to Many DOTs' requirements for the time of curing application, curing compounds should be applied as soon as the concrete surface finishing operations are completed [27-29]. TxDOT also states that curing compounds should be applied after concrete surfacing operations or immediately after bleeding sheen has disappeared and a second layer of coating should be applied within 30 minutes after concrete surfacing operations [30].

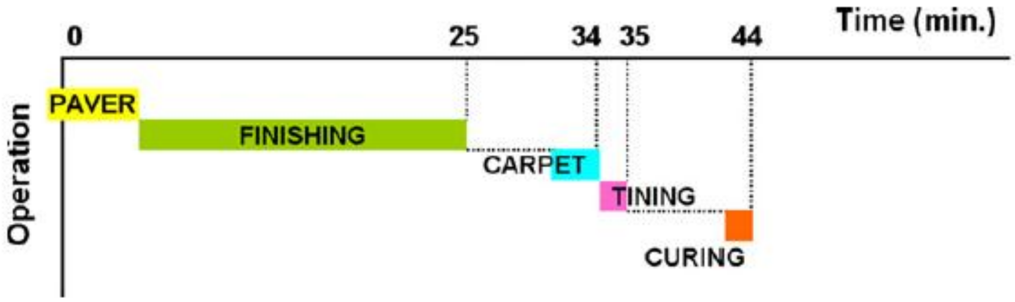

Figure 2-6 Timeline of finishing operations for a project in Texas [5]

The schematic diagram shown in Figure 2-6 represents the timeline of concrete surface finishing operations for a project in Texas [5]. It is shown that it took about 40 minutes for the paver to finish paving concrete and the surface finishing operations before curing compounds are applied. Taking the time for the bleeding sheen to evaporate into consideration, the standard seems reasonable to order the curing application right after the completion of all the surface finishing operations. Researchers [17] also suggested that if curing compounds have to be applied before the disappearance of bleeding sheen, it is better to avoid the major bleeding event, then spray half of the curing compounds and apply the second half once the first layer is dry. This is in accordance with the operation described by TxDOT, which mainly aims at reducing the influence of the bleeding water on the effectiveness of curing compounds.

2.2.2.2 Rate of application

Research indicated that a better way to improve curing quality is to apply a higher rate of curing compounds [17]. Typically, the application rate of curing compounds ranges between 102 ft^2/gal and 204 ft^2/gal [19]. Based on some manufacturers' guidances, most curing compounds should be applied no more than 200 ft^2/gal in a single pass to avoid curing compounds running into low areas [10]. According to ACI 308 [4], two layers of curing compounds should be applied with a total rate of 200 ft^2/gal to ensure better coverage and uniformity; for deeply textured concrete surface, the application rate should be doubled compared to trowelled or floated surface, which requires two passes of application, each at a rate of 200 ft^2/gal. An equation shown in Equation 2-1 [10] was also developed for adjusting the rate of application for textured surface to compensate for the increased area,

$$AR = (AR_{ungrooved}).\frac{(S+W)}{(S+2D+W)} \tag{2-1}$$

Where:

AR = the adjusted application rate (ft^2/gal),

$AR_{ungrooved}$ = the specified application rate for an un-grooved surface,

S = the space between grooves,

W = the width of the grooves, and

D = the depth of the grooves

Many DOTs require that the maximum rate of a single application should be no more than 150 ft^2/gal [27-29]. However, some other state DOTs have their own requirements for the application rate of curing compounds. For instance, TxDOT regulates a double-application of curing compounds where each application has a rate of 180 ft^2/gal for textured concrete surface [30].

2.2.2.3 Uniformity of application

Besides the time and the rate of application of curing compounds, the uniformity of application is also a concern regarding the quality of concrete curing practices. Research funded by Minnesota's Department of Transportation [25] showed that the uniformity of curing compounds was strongly affected by the curing compound spraying technology on a spraying machine, such as the spray nozzle type (including spray pattern, droplet size, pump pressure, spray angle and flow rate), nozzle spacing and boom height, nozzle orientation, cart speed and wind shield. It was also indicated that the non-uniform coverage of curing compounds was mainly caused by the wear and damage of nozzle orifice; therefore routine checkups on nozzle tips is required to maintain the utility of nozzles [25]. An illustration of a spraying machine is shown in Figure 2-7.

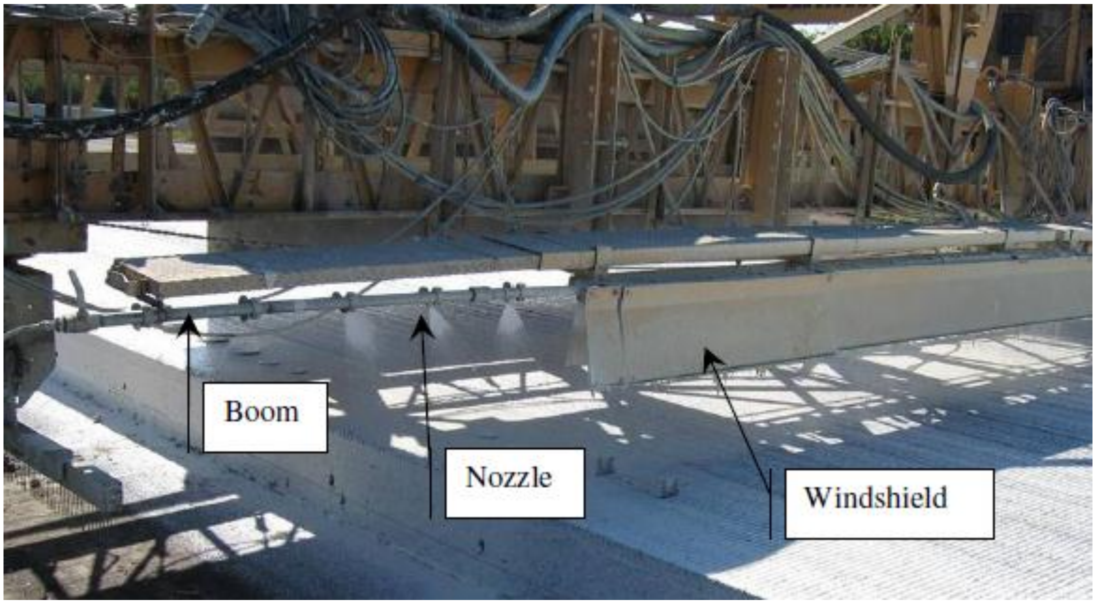

Figure 2-7 An illustration of a spraying machine [31]

Literature suggested that no method was available to verify the uniformity of non-pigmented curing compounds, but two methods were useful for white pigmented compounds [10]. One of the simplest methods is visual inspection: the inspector should look for areas have less white appearance; any appearance of gray indicates serious non-uniform application [10]. Another method is the application of a portable reflectometer [32], which uses a photocell to measure the intensity of light reflected from the concrete surface applied with curing compounds. The intensity of reflected light perpendicular to the surface of concrete is measured and data are evaluated based on the whiteness of the curing compounds where the whiteness is proportional to the application rate of curing compounds: whiter concrete surface reflects more light and corresponds to higher application rate of curing compounds [32]. The uniformity of the applied curing compound for a concrete pavement section is evaluated based on the overall whiteness condition on the surface of the section.

2.3 Curing Compound Effectiveness Evaluation Approaches

Extensive researches have been conducted to investigate approaches for assessing the effectiveness of curing compounds during the past few decades. This section summarizes some of the available approaches and discusses their utilities for evaluating the effectiveness of curing compounds.

2.3.1 Moisture Retention Test

Moisture retention test is described by the standard test, ASTM C 156, "Standard Test Method of Water Retention by Concrete Curing Materials" [24], focuses on testing moisture retention capability of curing compounds inside an environment-controllable chamber that has a potential evaporation rate ranges from 0.65 to 1.1 kg/m^2/hr. (0.133 to 0.225 lb./ft^2/hr.).

The method is straightforward, but the precision of it is not reliable. As indicated in the precision statement of the method, the standard deviation between laboratories is 0.30 kg/m^2 (0.06 lb./ft^2) which leads to a 54.5% of coefficient of variance compared with the standard limit of moisture loss rate at 0.55 kg/m^2 (0.113 lb./ft^2) [25]. Such high level of variability makes it difficult to confirm whether a curing compound has met the standard or not. The standard deviation within a laboratory is 0.13 kg/m^2 (0.03 lb./ft^2), which yields a better precision than that of the tests conducted between laboratories [25]. However, it is indicated that the precision of the tests conducted between laboratories is the controlling factor for the acceptance and the use of curing compounds. Many factors contribute to the poor precision between laboratories, such as the precision of controlled temperature, wind speed, time of application and rate of application of curing compounds, etc. [17].

Besides the deficiency of precision, moisture retention test is also limited to fixed ambient condition and single application rate of curing compounds under a laboratory environment, whereas concrete pavements under a field environment are subjected to different combinations of various conditions. Many state departments of transportation modified the standard test requirements and made their own standards. These modifications include using different mortar mixtures and specimen sizes, changing temperature and relative humidity in the testing chamber, using fans and lamps to mimic windy and sunny conditions and changing formulas of calculating moisture loss results [19]. However, the inapplicability of moisture retention test under a filed environment prevents its direct application.

2.3.2 Compressive Strength Test and Splitting Tensile Strength Test

Results of compressive strength tests are often correlated with curing effectiveness of concrete. In a research carried out by Wang [18] on the topic of evaluating curing effectiveness of concrete pavements, compressive strength tests were conducted on 2-in diameter and 4-in height concrete cylinders applied with different qualities of curing compounds. Results indicated that specimens applied with curing compounds showed better strength improvement compared to specimens without curing compounds treatment. However, the change of application time of curing compounds which was believed to influence the curing quality did not show significant effect on the compressive strength of specimens. This was explained by that the compressive strength test was not sensitive enough to the strength differences at the surface concrete caused by changing application time of the curing compounds [18].

Similar compressive strength tests were conducted by Whiting and Snyder [33] to evaluate the effectiveness of curing compounds. They also indicated that curing compounds treated specimens did show significant higher compressive strength than uncured specimens. It was also suggested that specimens applied with higher application rates of curing compounds showed higher compressive strength than specimens treated with lower application rates of curing compounds. Large variances were also observed from the compressive strength data. Besides, the author tried to correlate moisture loss measurements with compressive strength results and found that specimens with higher moisture loss generally tended to have lower compressive strength, which was sensible because a lower curing quality associated with a higher moisture loss measurement would result in higher concrete surface porosity and a lower concrete strength.

Splitting tensile strength tests were also performed to assess the quality of curing compounds. Literature suggested that large variations were found in the splitting tensile strength tests which made it hard to relate the results to the quality of curing compounds [34]. Another source [35] concluded that changing application rate of curing compounds did not have substantial effect on tensile strength of concrete slabs in terms of the splitting tensile strength test results.

2.3.3 Abrasion Resistance Test

Concrete surface abrasion resistance is considered to be affected by curing practices [17]. Because curing compounds are applied at the surface of concrete, it is assumed that the properties of concrete at near surface area will be influenced by the quality of curing practices. Research done by White and Husbands [34] showed promise of using core barrel abrasion test method to indicate the curing effectiveness. This test was performed by using a linear variable differential transformer (LVDT) to measure the depth into concrete surface created by a rotating diamond-core barrel attached to a drill press. Abrasion resistance tests were conducted on specimens cured under different curing conditions. Results of specimens cured with curing compounds were very similar to those of moist-cured specimens in terms of the rate and the final depth of the abrasion tests; specimens without any curing practice showed higher rate of abrasion and deeper final depth at the end of abrasion tests as expected. Because of the time constraint, the research did not investigate the concrete surface abrasion resistance test more thoroughly. It was recommended that more types of curing compounds should be evaluated to better understand the utility of this test. In general, this test was considered less time-consuming compared with some other methods and further investigation was suggested.

2.3.4 Rapid Chloride Permeability Test

Rapid chloride permeability (RCP) test was conducted by Whiting and Snyder [33] in the study of evaluating effectiveness of curing compounds. Typically, RCP test uses the amount of charge passed through specimens to represent the permeability of specimens. The idea of the test was to relate the permeability of concrete to the curing quality of curing compounds. It was considered that a better curing quality could lead to better hydration of concrete and lower porosity at the surface of concrete, thus would result in a lower permeability of concrete. Specimens applied with different curing practices were tested under different ages. Results showed that for 3-day age specimens, the uncured ones and the low quality curing compound cured ones showed similarly high permeability; the high quality curing compound cured specimens showed significant low permeability. The permeability of 10-day age and 28-age specimens also showed similar phenomena, though inconsistent results were observed for 28-day age specimens where uncured specimens showed lower permeability than specimens applied with curing compounds. Generally, RCP test showed good utilities to assess the effectiveness of curing compounds.

2.3.5 Temperature-based Maturity Concept

The temperature-based maturity concept is based the assumption that higher temperature would accelerate the hydration rate of cement and increase the strength of concrete at early ages [4]. Maturity is a function of temperature of concrete and elapsed time since the mixing of cement with water, as expressed in Equation 2-2 [36]:

$$M = \sum_{0}^{t} \left(T - T_0 \right) \cdot \Delta t \tag{2-2}$$

Where:

M = maturity index, ℃-hours (or ℃-days),

T = average concrete temperature, ℃, during the time interval *Δt*,

To = datum temperature (usually taken to be -10 ℃),

t = elapsed time (hours or days), and

Δt = time interval (hours or days)

A field investigation was conducted by Wang, Cable and Ge [26] in a concrete pavement construction project in Iowa to evaluate the utility of the temperature-based maturity concept for predicting curing effectiveness. The field investigation was conducted on concrete pavements consisting of curing compounds treated sections, uncured sections and wet-cured sections which were covered with wet burlap and sheets. During the field investigation, the temperature at top, middle and bottom positions of the concrete pavements were measured every two hours for seven days using thermocouples. The results showed that the temperatures for pavement sections applied with curing compounds were generally lower than the uncured sections and the wet-cured sections. Maturity indexes were calculated for the pavement sections applied with various curing practices. It was assumed that the temperature-based maturity concept would show the utility to distinguish the quality differences of the curing practices regarding their capabilities to improve concrete hydration and strength development. However, it was probably due to the fact that the temperature-based maturity concept did not consider the influence of moisture conditions on the hydration of concrete, the results did not show significant differences between wet-cured and uncured pavement sections regarding their maturity indexes. Therefore, it was suggested that the temperature-based maturity concept was not an efficient way to evaluate the effectiveness of curing under field conditions [26].

2.3.6 Electrical Conductivity

In the same investigation conducted by Wang, Cable and Ge [26] as mentioned before, electrical conductivity tests were also performed under both laboratory and field conditions. Electrical conductivity tests were conducted using a pair of copper plates which were vertically inserted into concrete near the surface layer and a conductivity meter was used to record the resistivity between the two plates. Presumably, electrical conductivity would be greatly affected by the mobility of the ions in concrete. As the amount of the free water inside the concrete diminish due to surface moisture evaporation and concrete hydration, the amount of the mobile ions also decreases which causes the reduction of the electrical conductivity. Since curing practices affect the evaporation of concrete surface moisture and concrete hydration process, it is reasonable to relate the electrical conductivity with the effectiveness of curing compounds.

The test results under laboratory conditions implied that electrical conductivity of concrete was very effective in distinguishing curing quality between wet-cured, air-cured and oven-cured specimens. The wet-cured specimens had the highest electrical conductivity and oven-cured specimens had the lowest which was as expected. The results also noted that higher quality curing compounds generally yielded higher electrical conductivity compared to lower quality curing compounds and specimens treated with a double-layer of curing compounds yielded slightly higher electrical conductivity than specimens sprayed with a single-layer of curing compound. Under laboratory conditions, electrical conductivity of treated specimens generally showed a strong relationship with the moisture content within the surface of concrete, therefore the authors concluded that electrical conductivity measurements might be useful to estimate the effectiveness of different curing compounds regarding their capability to retain moisture at the near-surface area of concrete [26].

Electrical conductivity measurements were also made under field conditions in the concrete pavement construction project in Iowa as mentioned before [26]. During the field investigations, copper plates were also inserted into the top and middle layers (1-in and 6-in below the surfaces of pavements, respectively) of concrete pavements to collect conductivity measurements. The conductivity of the top and the middle layers of concrete were measured and it was believed that the smaller the differences of electrical conductivities between the top and middle layers, the better the effectiveness of the curing compound. The results showed that conductivity measurements decreased with time and the variation of the measurements in the top layers was smaller than the variation in the middle layers. However, some of the measurements in the middle layers showed large variation after 60 hours. It was considered that the decreasing trend of the conductivity in the top layers was mainly due to the evaporation of the surface moisture, which was thought to be affected by the effectiveness of curing compounds.

As for the effect of various curing practices, results showed that wet-cured sections had the highest conductivity as expected, as there was a distinguishable difference between the wet-cured and the uncured sections. The sections sprayed with curing compounds showed lower conductivities than the wet-cured sections and higher conductivities than the uncured sections, which was reasonable. In their project report [37] where the conductivity measurements of all the tested sections were included, it was found that even though the conductivity measurements of sections applied with various curing compounds fell into the boundaries between the conductivity measurements of wet-cured and uncured sections, which made sense, it was still hard to differentiate which curing compound was better, mainly because that there were many overlaps between the trends of the conductivity measurements of different curing compounds. The authors tried to use another trend line, which was obtained by subtracting the initial conductivity value from the current conductivities at different time points to represent the effectiveness of each curing compound. The smaller the difference of the conductivities, the better the curing practices. Though this method showed some utilities, it was reported that the newly derived trend was highly dependent upon on the initial conductivity value, and if the initial measured conductivity value was off, erroneous conclusions concerning the curing effectiveness could be drawn (the uncured section was found to be cured the best according to this method, which made no sense). It was suggested by the authors that more tests should be conducted to verify this method.

2.4 Dielectric Property of Concrete

Dielectric materials refer to non-conducting materials or the semi-conducting materials that can store potential energy [38], and Portland cement concrete is often considered as a dielectric material since it meets the criteria. A dielectric material usually exhibits both electric and magnetic properties; the former one is described as permittivity and the latter one is named as permeability [39]. Due to the insignificant existence of magnetic permeability of materials, the portion of magnetic property is negligible, remaining electrical permittivity to be the only interest of the investigation on dielectric materials [40]. The permittivity property of a dielectric material describes the ability of the material to allow the passing through of electric fields or a current, and the permittivity of free space is usually combined into the electric flux density function as described below [41]:

$$D = \varepsilon_0 E + P \tag{2-3}$$

Where:

D = electric flux density, C/m^2
ε_0 = permittivity of free space, 8.85 x 10^{-12} F/m
E = electric field intensity or strength, V/m
P = induced polarization, C/m^2

If the material is assumed to be linear and isotropic through which the electric field is passing, then a proportional relationship between the electric field and THE induced polarization is expressed as [42]:

$$P = \chi_e \varepsilon_0 E \tag{2-4}$$

Where:

χ_e = dimensionless electric susceptibility

Then Equation (2-3) becomes:

$$D = \varepsilon_0 \left(1 - \chi_e\right) E \tag{2-5}$$

It is also known that:

$$D = \varepsilon E \tag{2-6}$$

Therefore:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \left(1 - \chi_e\right) \tag{2-7}$$

Where:

ε_r = relative complex permittivity (dielectric constant)

ε = complex permittivity of a material

Dielectric constant 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 [43]. Typical dielectric constant values are given in Table 2-1 [40, 44]:

Table 2-1 Typical dielectric constant range for materials [40, 44]

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 above table, water has the largest dielectric constant among the typical materials. Researchers found that dielectric constant might be able to serve as an indicator of the amount of unbound free moisture content for given aggregate-constituted materials [43]. Therefore, dielectric constant may also have certain relationship with the unbound free moisture within concrete mixtures.

Because concrete is a mixture of a couple of constituents that have different properties, it is therefore considered as a composite material [45]. Theoretically, each constitute of the composite should maintain their individual property, but concrete is an exception because of the chemical reactions between cement and water during the concrete hydration process [1, 45]. As a result of the chemical reactions, the amount of each portion of the composite would change, i.e., the amount of capillary water inside the concrete diminish with time due to the self-desiccation process driven by concrete hydration and the evaporation process caused by potential evaporation of ambient environment [31]. Figure 2-8 shows diagrams of volumetric changes of different portions of concrete due to hydration.

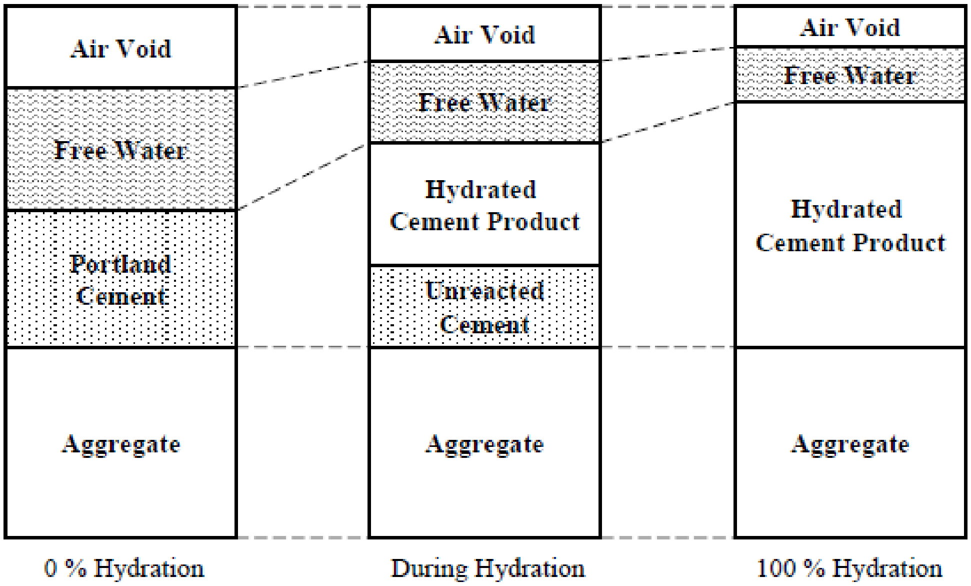

Figure 2-8 Changes of different portions of concrete due to hydration [46]

In recent years, research has been conducted to investigate the dielectric constant of concrete at early ages when the change of free water content is most dramatic along the whole hydration process. Dielectric constants have been considered by researchers to be very closely related to the free water content in the concrete [39, 46, 47]. Because of the significant sensitivity of dielectric constants to water content within materials, dielectric constant measurements made at different time points for a single material are able to reflect the volumetric change of the unbound free water with time. Generally, higher dielectric constants were observed in the earlier age of the concrete. With the progress of hydration process moisture evaporation, the free water within the concrete decreased with time. Correspondingly, the measured dielectric constants showed decreasing trends as time elapsed [39, 46].

3. INVESTIGATION APPROACH

As mentioned in Chapter 2, current available standards that consider the use of the moisture retention test to characterize the effectiveness of curing compounds have intrinsic limitations. Researchers have found some utilities to relate some specially measured properties of concrete (e.g., permeability, maturity and electrical conductivity) to the effectiveness of curing compounds; however, their application still showed practical limitations unless a more concise measure could directly indicate the effectiveness of curing compounds under field conditions as discussed in Chapter 2. This chapter provides detailed descriptions of the approaches involved in the proposed protocol for assessing the effectiveness of curing compounds.

3.1 Relative Humidity (RH) Measurement and Effectiveness Index (EI)

In this study the quality of curing compounds was assessed by a single parameter named as the effectiveness index (EI). EI is determined based on the moisture-modified concrete maturity concept(as shown in Equation 3-2) using relative humidity (RH) and temperature data that are taken by an ATEK Concrete Maturity Meter (ACMM) system (manufactured by ATEK Co. in Dallas, Texas) under both laboratory and field conditions. A detailed view of an ACMM system is shown in Figure 3-1.

The ACMM system consists of three relative humidity sensors arranged to measure ambient RH and RH inside the two separate chambers of the curing plate (which is placed on top of bare concrete) as shown in both Figure 3-1 and Figure 3-2. The RH sensors are of the chilled mirror hygrometer type, and sometimes refer to an optical condensation hygrometer which is the most accurate, reliable and fundamental hygrometer commercially available. As a result, this type of sensor is widely used as a calibration standard.

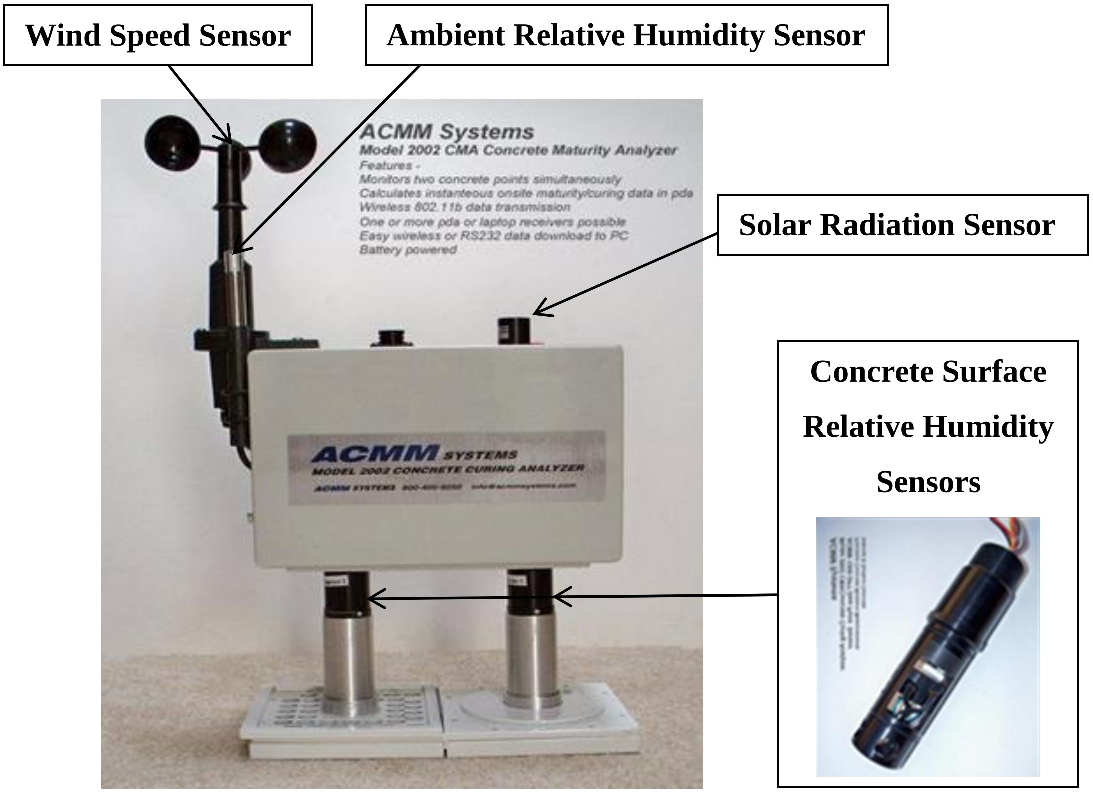

Figure 3-1 The ACMM system

Figure 3-2 shows pictures of the top and bottom views of the curing plate which consists of two separate chambers – one is sealed and the other one is filtered. The filtered side is covered by a layer of fine screen mesh first to prevent concrete mortar from leaking into the small holes.

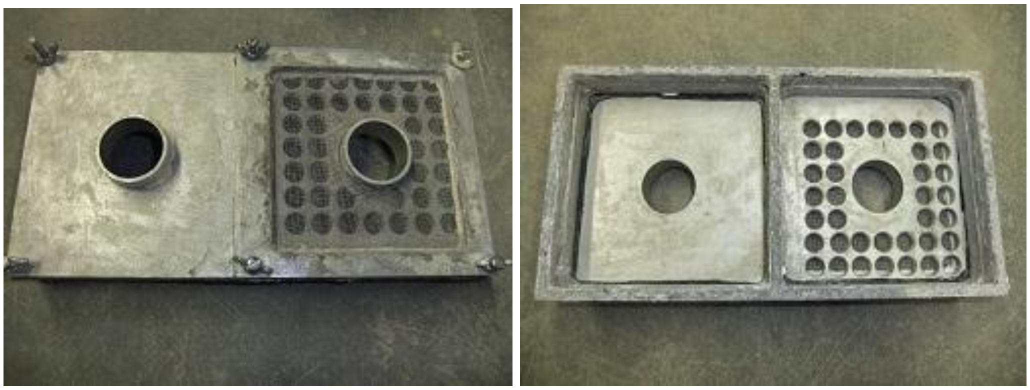

Figure 3-2 Top and bottom view of the curing plate

As shown in Figure 3-3, a thin layer of concrete mortar is applied on top of the fine screen mesh on the filtered side. The two housing holes on each side are then covered and both chambers are tightly placed on bare concrete surface and sealed with silicon sealant before curing compounds are sprayed. The two chambers provide environment that are large enough for moisture to be sampled by the RH sensors of the ACMM system which is installed on the housings after the curing compounds are applied. The sealed side represents a near perfect curing condition; the surface of the filtered side after being covered by a thin layer of concrete mortar on which curing compounds are sprayed, is subject to the vapor pressure created by the bare concrete inside the filtered chamber below the applied curing membrane, which essentially provides a representation of the curing condition near the surface of the concrete. The chilled mirror sensors are the most suitable type of sensor to measure the relative humidity at the levels that develop within the sampling chambers.

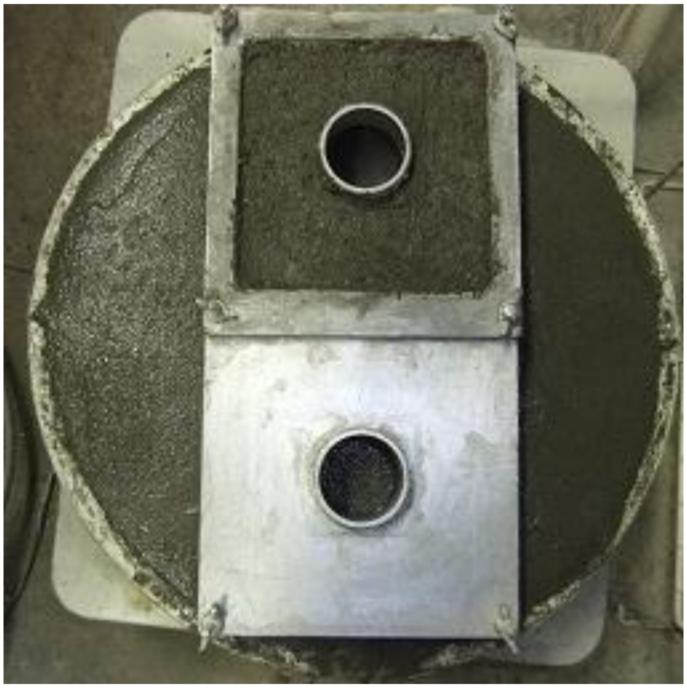

Figure 3-3 Curing plate sitting on a concrete specimen

Once curing compound is sprayed, the sensors of the ACMM system are inserted into the two housing holes on each side of the plate to measure RH data. The setup of the ACMM system is shown in Figure 3-4. The ACMM system also monitors wind speed and solar radiation, which are two important factors that affect moisture evaporation and curing quality under field conditions.

Figure 3-4 The ACMM system standing on a concrete specimen sprayed with curing compound

Once the RH data from the sealed, filtered side of the plate and the ambient environment are taken by the ACMM system as shown in Figure 3-5, the effectiveness index (EI) is then calculated based on the moisture-modified maturity concept.

Maturity, as mentioned in the previous chapter, is a parameter that relates to the temperature and the age of concrete, and has been mainly used as a non-destructive method to predict concrete strength development for decades. As was shown in Equation 2-2, maturity is a function of the elapsed time and the measured concrete temperature. It has already been indicated that the temperature-based maturity model is not an efficient indicator of the curing effectiveness [26], therefore a moisture-modified maturity function is considered in this study [15]. A moisture modification factor was developed for numerical computation of the influence of moisture on equivalent concrete curing time [48] based on the observation that concrete hydration completely ceased when the RH dropped to approximately 80%. Because of the advancement of related technologies for measuring moisture, it was discovered later that concrete strength still slowly increased even when the RH was below 80%. Therefore, this moisture modification factor was improved by adjusting the coefficients in the model as shown in Equation 3-1 [49]:

$$\beta_H = \left[1 + \left(a - aH\right)^b\right]^{-1} \tag{3-1}$$

Where:

β_H = the moisture modification factor,
H = the relative humidity of concrete,
a = adjusted coefficient, changing from 7.5 to 5, and
b = adjusted coefficient, changing from 4 to 1

The moisture modification factor represents the effect of moisture on the rate of hydration reaction. It was suggested that the temperature-based maturity could be adjusted by adding the moisture modification factor into the maturity function as shown in Equation 3-2 [15]:

$$M_H = \beta_H \cdot \sum_0^t \left(T - T_0\right) \cdot \Delta t = \frac{\sum_0^t \left(T - T_0\right) \cdot \Delta t}{1 + \left(5 - 5H\right)} \tag{3-2}$$

Where:

M_H = the moisture-modified maturity at age t of concrete
T = the average concrete temperature, ℃, during time interval Δt
To = datum temperature (usually taken to be -10 ℃),
t = elapsed time (hours or days), and
Δt = time interval (hours or days).

In this study, the curing effectiveness index (EI) is introduced based on the use of the moisture-modified maturity model. The moisture-modified maturity of concrete M_H is now represented by t, where t is the equivalent age of concrete, and the EI is then calculated as shown in Equation 3-3:

$$EI = \frac{t_f - t_a}{t_s - t_a} \tag{3-3}$$

Where:

t_f = the equivalent age of concrete under the filtered side curing condition,

t_s = the equivalent age of concrete under the sealed side curing condition, and

t_a = the equivalent age of concrete under the ambient curing condition

All the data needed for calculating the equivalent age of concrete under different curing conditions (i.e., filtered, sealed and ambient curing conditions) are recorded by using the ACMM system. Figure 3-5 shows a typical laboratory data set recorded by the ACMM system and processed using Excel spreadsheet.

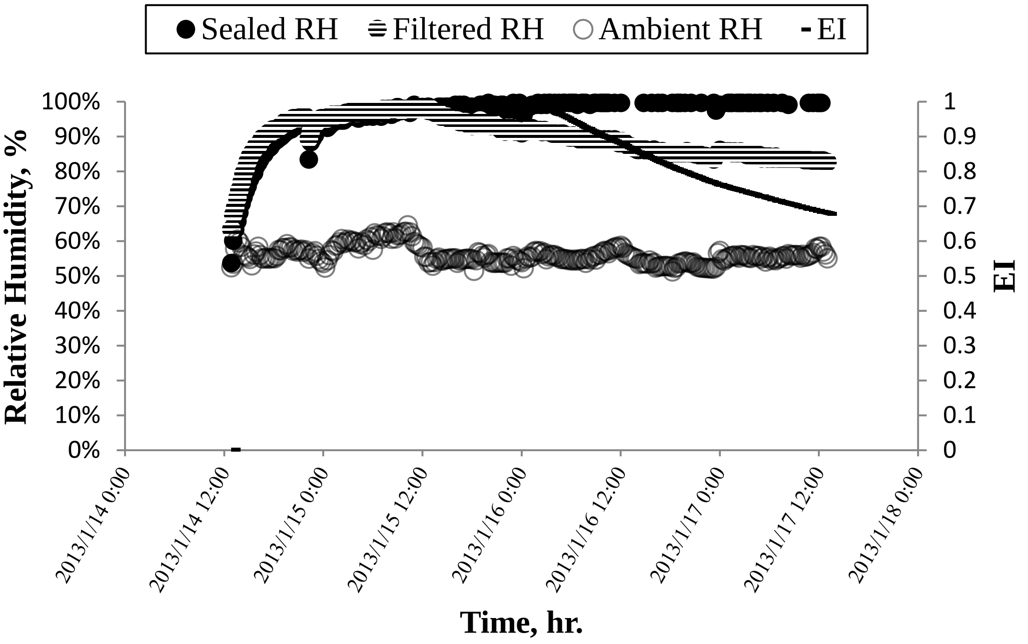

Figure 3-5 An example of RH data taken by the ACMM system

As shown in Figure 3-5, the RH in both the sealed and filtered side of the plate gradually increased to 100% after approximately 12 hours of measuring; the ambient relative humidity in the laboratory condition was controlled at about 50%. The RH measured in the filtered side of the plate started to decrease after a certain period of time which highly depended on the quality of the curing compound that was sprayed at the surface of the concrete mortar covering the top of the filtered side of the plate as shown in Figure 3-3. The better the quality of the curing compound, the longer the RH in the filtered side of the plate maintains at a high level and the higher the EI that would be obtained at the end of the measurement. Since laboratory tests last for 72 hours, the values of EI at 72 hours are evaluated for specimens sprayed with different qualities of curing compounds.

3.2 Concrete Surface Abrasion Resistance Test

Since the zone of concrete that is affected by the curing compound is only the top few inches of the concrete surface, the attempt to use compressive strength test which represents the entire concrete strength of a specimen to evaluate the effectiveness of curing compounds is unconvincing. Although the literature showed some effects of curing compounds on increasing the compressive strength of specimens, a test to better represent the strength of curing affected zones should be performed. To this end, this study considers conducting surface abrasion resistance test and using abrasion weight loss of specimens to present the strength of surface concrete.

The concrete surface abrasion resistance test is based on ASTM C944 [51]. This test determines abrasion resistance of the surface concrete by measuring the weight loss of the concrete abraded by a rotating cutter in a given time period. The cutter consists of a series of dressing wheels mounted on a rod that is attached to a drill press. Figure 3-6 shows a picture of the cutter head bearing on a specimen and a drill press.

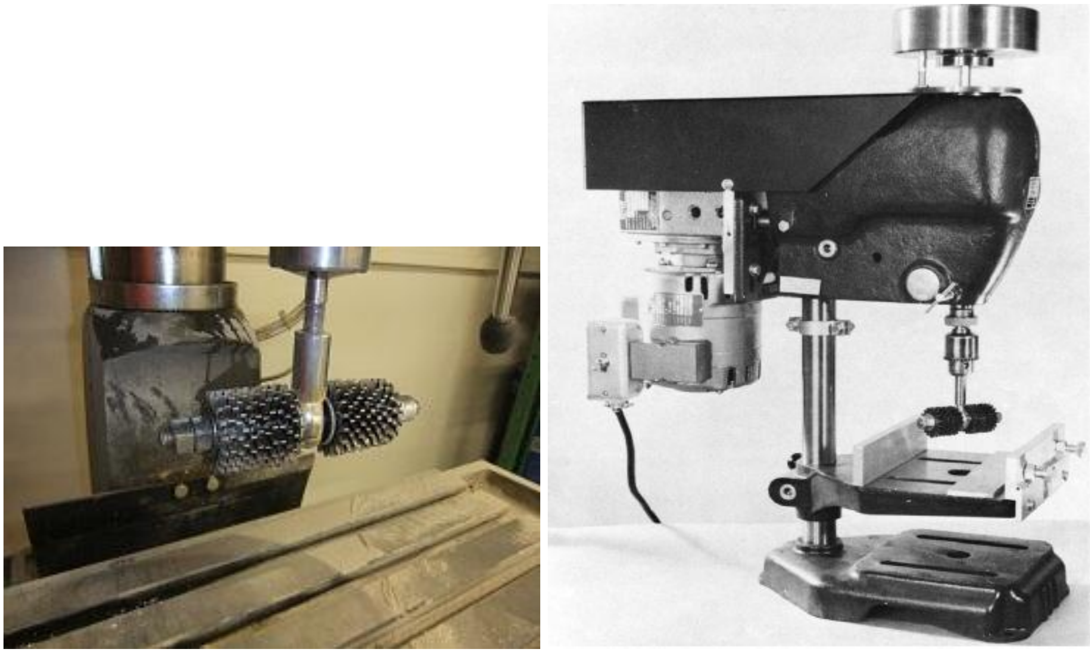

Figure 3-6 ASTM C944 abrasion resistance test cutter head and the drill press [50]

Surface abrasion resistance test for this research is performed on the surface of a 12-in diameter concrete cylinder which is also used to perform relative humidity measurements taken by the ACMM system as shown in Figure 3-4. Once the measuring of relative humidity data are finished after 72 hours, the curing plate is taken away, leaving two blocks of bare concrete as shown in Figure 3-7. The block at the right side was under the sealed side of the plate, which was considered under a perfect curing condition. The block at the left side was under the filtered side of the plate, which was subjected to the influence of the curing compound that was applied at the surface of the thin layer of concrete mortar covering on the filtered side of the plate. The abrasion resistance test was performed on the filtered side to evaluate the effect of applying curing compounds on the strength development of the surface concrete.

A drill press is used to apply a constant force through the cutter into the surface of specimens and to rotate the cutter at 200 revolutions per minute. In the research, a constant load of 22 lbs. was applied on the drill press, and each test was performed for 10 minutes. A concrete specimen was weighted before and at the end of an abrasion resistance test to determine the weight loss through the abrasion process.

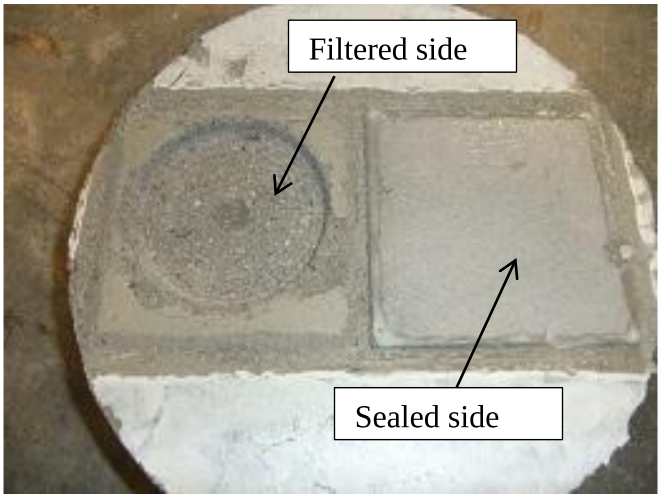

Figure 3-7 Tested specimen using the abrasion resistance test

The idea of performing this test is because it is a commonly known fact that as the strength of surface concrete increases, the resistance to abrasion also increases. A lower weight loss of the abrasion test indicates a higher strength of surface concrete, which is probably due to a better curing practice. Therefore, this test provides a means to validate the utility of EI which represents the quality of a curing compound by correlating it to concrete surface abrasion resistance.

3.3 Dielectric Constant (DC) Measurement

The curing practices have influence on the hydration process of concrete by moderating excessive evaporation of the free surface moisture and maintaining a favorable relative humid environment. Intuitively, it may be possible to correlate the effectiveness of curing compounds to the volumetric change of the free water at the concrete surface. It was already discovered by researchers [46] that the dielectric constant is directly related to the free moisture content and the degree of hydration of concrete. Therefore by observing the changes of measured the dielectric constant with time for early-age concrete, correlations may be established between the dielectric constant and the effect of applying curing compounds on maintaining free moisture at concrete surface. This provides a means to evaluate the moisture retention capability of curing compounds in terms of the measured dielectric constant.

The rate of the volumetric change of free concrete surface moisture may reflect the effectiveness of applied curing compounds; dramatic reduction of the volume of free moisture within a specific period indicates a low effectiveness of curing compound and a lower rate of reduction of the volume of free moisture represents a better curing practice.

The measuring of dielectric constant is conducted by using an Adek^{TM} Percometer as shown in Figure 3-8 [51]. The device consists of two parts; one part is the probe for measuring the dielectric constant and the other part is the main body of the device with a screen showing the measured dielectric constant.

Figure 3-8 The Adek^{TM} Percometer and the probe [51]

The specifications of the Percometer is shown in Table 3-1 [51].

Table 3-1 Specifications for the Adek^{TM} Percometer [51]

Probe type	Measuring range			Accuracy of ε_r measuring	Recommended Application
	Dielectric constant (ε_r)	Electrical conductivity, $\mu S/m$	Temperature, $^\circ$C		
Surface Probe	1 ~ 32	0 ~ 2000	-40 ~ +80	$\pm 0.1+1\%$	Laboratory use, Tube Suction Test

The Adek^{TM} Percometer allows easy and instant measuring of dielectric constant of materials. Therefore, it could provide a means to extend the curing compound effectiveness evaluation of the ACMM system over a wide area of pavements rather than just a single position. Under a field investigation, this approach considers the use of dielectric constant measurements to represent the curing quality of areas near the location where the ACMM system is placed. This supplements the evaluation of the curing compounds effectiveness represented by EI.

Under laboratory conditions, the measurement of the dielectric constant is made at the surface of a 6” diameter and 2” high concrete cylinder. Once fresh concrete is filled into the cylindrical mold, a set of plastic tube coupling is placed at the surface of concrete as shown in Figure 3-9.

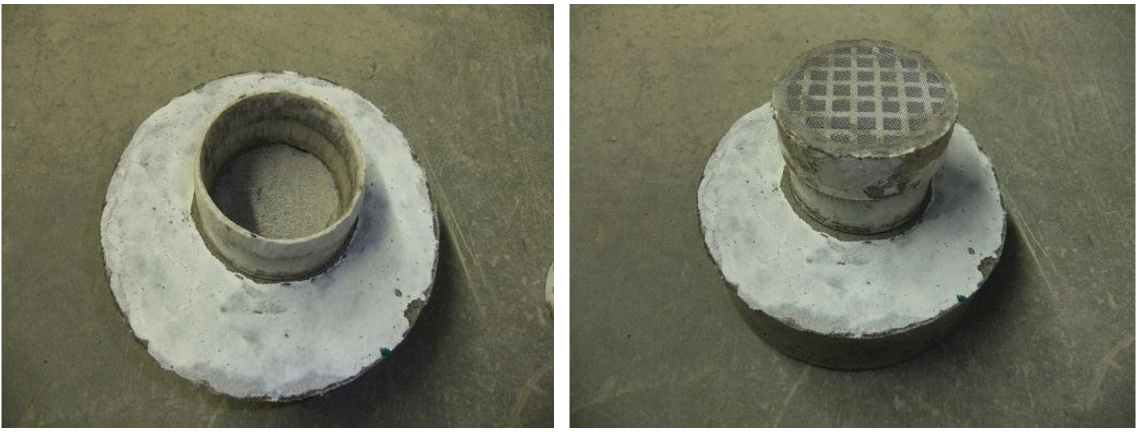

Figure 3-9 Dielectric constant measurement setup

As shown in Figure 3-9, the bottom part of the tube coupling is first placed on the surface of the concrete before the curing compound is applied. The rim of the plastic tube is sealed using silicon sealant to prevent curing compounds that are applied outside from flowing into the bare concrete surface inside the tube.

The top part of the tube coupling is designed as a cap to cover the bottom part of the tube in case of any air or moisture leaking. The top part of the cap is filtered, and is covered by a layer of fine screen mesh first to prevent concrete mortar from leaking into the holes. The function of the cap is the same as the filtered side of the plate for relative humidity measurements. A thin layer of concrete mortar is applied on top of the cap to cover the hole and will serve as a medium to retain curing compounds. Then the top part of the coupling is covered on the bottom part as shown in Figure 3-9 before curing compounds are applied.

Figure 3-10 Curing compounds applied on dielectric constant measuring specimen

As shown in Figure 3-10, curing compounds are applied at the concrete surface both around the side of the tube coupling and at the surface of the thin layer of concrete mortar that has been applied on top of the cap, and the concrete inside the tube remains bare. The dielectric constant of concrete can be easily measured by taking off the cap and inserting the probe into the tube to implement the measuring process at the surface of the bare concrete. This setup provides an indirect way to measure the dielectric constant of the curing compound affected area which is the bare concrete inside the tube, without damaging the curing compound membrane applied at the surface of concrete.

Figure 3-11 shows an example of the decreasing trend of dielectric constant measurements with time. The test that produced these results was conducted at a controlled temperature (32 ± 1 ℃) and relative humidity (50 ± 5%) environment without wind effect, and a curing compound was applied to the specimen at 220 ft^2/gal application rate.

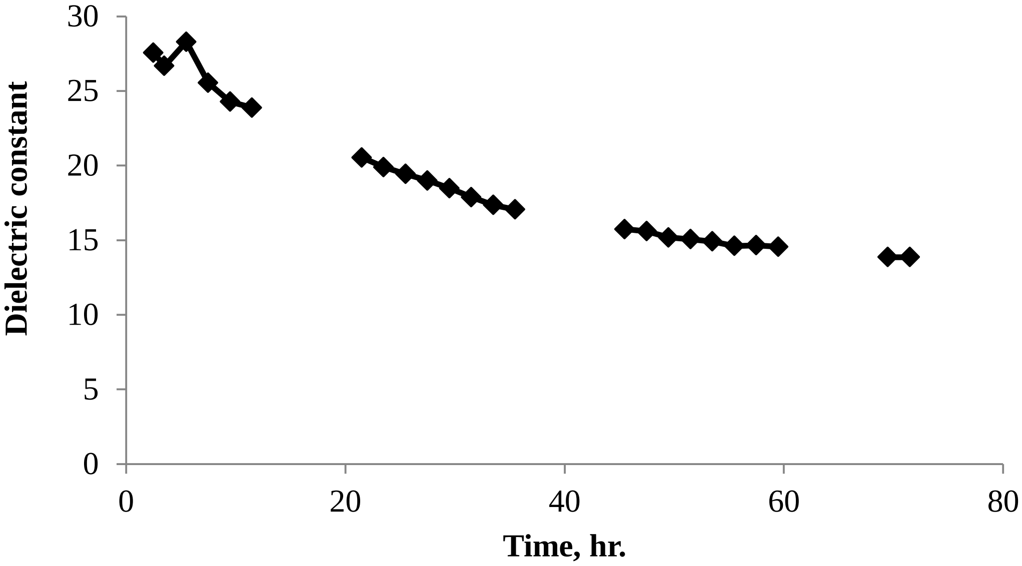

Figure 3-11 An example of dielectric constant measurements

3.3 Moisture Retention Test

The moisture retention test measures the moisture loss of a concrete specimen within a given period of time using a high-sensitivity scale with 0.1 gram of resolution as shown in Figure 3-12.

Figure 3-12 A high-accuracy scale

The test is based on the standard test, ASTM C 156, "Standard Test Method of Water Retention by Concrete Curing Materials" [24], which measures the water retention capability of curing compounds under a controlled environmental for concrete specimens. Regardless of the limitations of the water retention test as discussed in the previous chapter, such as high level of variance between laboratories and requirement of fixed ambient condition, it still provides a straight-forward method for assessing the moisture retention capability of curing compounds. Also the results of the measured moisture loss are used to validate the utility of EI for assessing the effectiveness of curing compounds in terms of moisture retention capability.

The environment chamber used for the test is controlled at a fixed temperature (32 ± 1 ℃) and relative humidity (50 ± 5%). Tests were made both with a no wind or a wind condition simulated by using a fan. The weight of specimens is recorded every one hour for the first 12 hours when the evaporation process is most rapid, and every couple of hours for the remaining 60 hours when the evaporation process becomes steady. The moisture loss of specimens is observed for 72 hours totally. The result is presented in the form of moisture loss percentage which is calculated from the moisture loss result divided by the total weight of the concrete specimen. A sample of the measurements is shown in Figure 3-13.

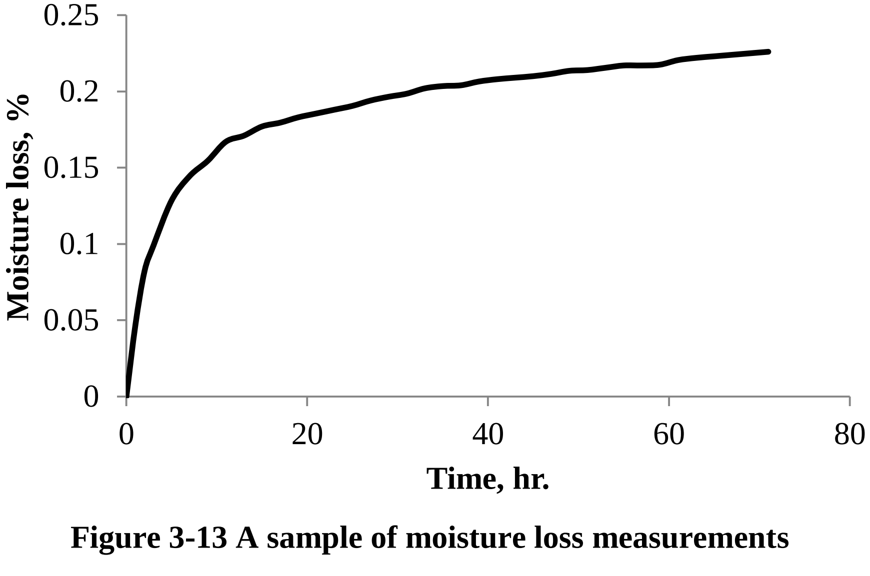

Figure 3-13 A sample of moisture loss measurements

After concrete reaches the final set condition, the moisture evaporation rate becomes constant and beyond that point it was found that curing practices made no significant difference on the evaporation process. Therefore, it is determined that the cumulative moisture loss measurements are made up to 48 hours in the research.

3.5 Laboratory Testing and Material Design

Materials for mixing concrete specimens consist of ASTM Type I Portland cement, concrete sand that meet the specification of ASTM C 33 and water. Mixture proportions are given in Table 3-2. Two different w/cs are used in the research. Concrete mixtures are mixed and prepared under laboratory conditions.

Mortar preparation and mixing are carried out using an electrically driven mechanical mixer according to ASTM C 305, "Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency" [52].

Two different molds are used. A 12-in diameter and 4-in height cylindrical mold is used to make concrete specimens for performing the tasks, including the measuring of relative humidity, moisture weight loss and surface abrasion weight loss. A 6-in diameter and 2-in height cylindrical mold is used for making specimens on which dielectric constant measurements are made.

Table 3-2 Mixture proportions

Mixture	**W/C**	**Unit Weight (lb./ft^3)**		
		Water	**Cement**	**Sand**
	0.4	15.38	38.45	105.75
	0.43	16.53	38.45	102.69

The research considers the use of a minimum of three different curing compounds in order to generate different levels of curing qualities. The classifications of the curing compound samples are listed in Table 3-3. Type 2 denotes white-pigmented curing compounds. Class B denotes the solids in the compounds are resin-based. In this research, WR Meadow 1250 curing compound is represent by a letter “A”, and WR Meadow 2250 curing compound is represent by a letter “B”.

Table 3-3 Classification of curing compounds to be tested

Manufacture/Designation	Type	Comments
WR Meadow 1250 (A)	Type 2—Class B	Normal Resin-based
WR Meadow 2250 (B)	Type 2—Class B	High Reflective
Sinak Relay	Lithium Based	

Table 3-4 Levels of the design variables

Variable	High Level	Medium Level	Low Level
Type of the curing compound	WR Meadow 2250	WR Meadow 1250	Lithium
Application Rate of compound, ft^2/gallon	120		220
w/c of concrete mixture	0.43		0.4
Wind speed, mph	5		0

Two levels of application rate are considered in this study, together with three types of the curing compounds and the w/cs of the mixture, the three main effects are evaluated throughout the testing program. The design variables are listed in Table 3-4. In addition, as part of bridging the gap between laboratory test and field exposure conditions, wind conditions are also considered under the laboratory condition. The wind effect is simulated using an industrial fan.

4. LABORATORY RESEARCH FINDINGS

4.1 Overview

Because of the inherent limitations (e.g. limited to fixed laboratory condition) of the current standard test, ASTM C 156, “Standard Test Method of Water Retention by Concrete Curing Materials” [24], a new laboratory protocol is proposed as shown in Figure 4-1. It consists of using several methods to assess the concrete curing effectiveness. Relative humidity results derived from the temperature measurements were used to calculate Effectiveness Index (EI). Moisture loss and abrasion resistance tests were conducted at the surface of concrete specimens only in laboratory conditions; they were performed to verify the utility of EI to represent the moisture retention capability of the curing compounds and to validate the strength development of the specimens. Also, dielectric constant (DC) measurements taken at the surface of specimens were useful to suggest free moisture content of concrete specimens and correlation was established between the measured DC and the effectiveness of the applied curing compounds in terms of the moisture retention capability.

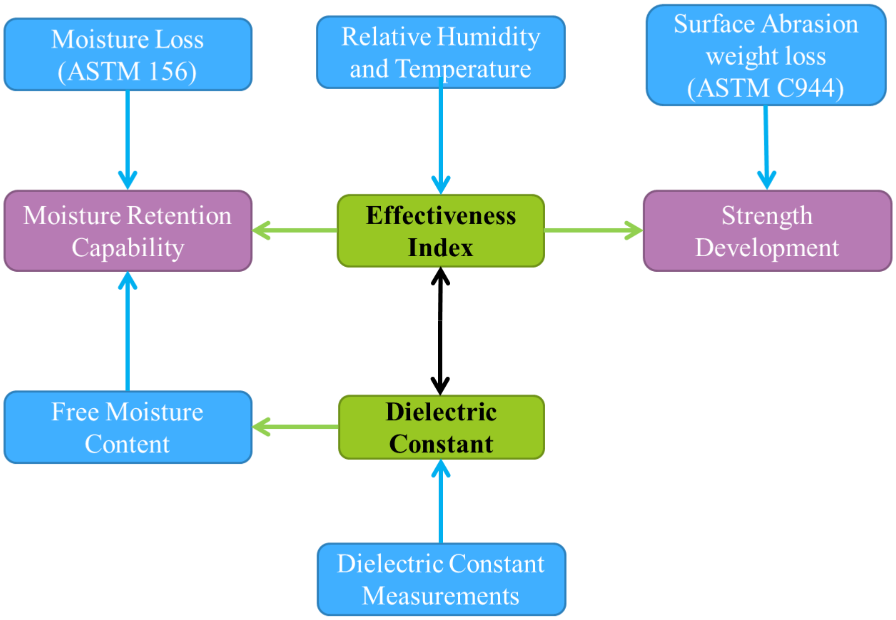

Figure 4-1 Laboratory research program flowchart

4.2 Evaluation of Effectiveness Index (EI)

This section presents a summary of the research findings of the experiments conducted in the laboratory on 12-in diameter and 4-in height concrete specimens. Relative humidity determinations based on temperature recorded by the ACMM system and moisture weight loss measurements were taken simultaneously on each one of the specimens, and concrete surface abrasion resistance tests were performed right after the completion of the first two tests. EI calculations were made based on the calculated relative humidity and temperature data and were correlated to the concrete surface abrasion resistance and the moisture weight loss measurements, in order to verify the efficacy of using EI to represents the moisture retention capability of the tested curing compounds. Sensitivity analyses of EI to various curing treatments were also conducted.

4.2.1 Validation of the Efficacy of EI

The proposed concrete curing Effectiveness Index (EI) is based on the moisture-modified maturity concept and is calculated using relative humidity and temperature data collected by the ACMM system as presented in Chapter 3. Essentially, EI is a ratio of the maturity of concrete under the filtered side of the plate where an actual curing condition is simulated, to the maturity of concrete under the sealed side of the plate where a perfect curing condition is presented; the maturity of the ambient curing condition calculated based on ambient temperature and moisture is also combined into the EI function by subtracting it from both the filtered side maturity and sealed side maturity as shown in Equation 3-3. The moisture-modified maturity is highly sensitive and is able to differentiate the subtle moisture and temperature changes affected by curing practices. As a result, a higher EI is expected to indicate a higher concrete moisture-modified maturity under the filtered side of the plate which is influenced by the type and the amount of the applied curing compound and the ambient environment affected by the surrounding temperature, moisture and wind condition.

In spite of the various types of curing practices, such as various types of curing compounds, different application rates of a curing compound and wind speed are expected to influence both the moisture potential evaporation rate and EI. In fact, EI should show certain relationship with the corresponding concrete surface abrasion weight loss and the moisture weight loss measurements which all are taken simultaneously for each single specimen.

In general, a better curing practice, for instance, the use of a better quality of curing compound or a higher application rate of curing compound would create a favorable curing condition for concrete hydration process and result in a stronger concrete especially in the top few inches of the surface concrete. Presumably, EI is a single parameter that is able to qualify the curing practices, i.e. the effectiveness of curing compounds. Therefore, a better curing practice which ideally causes better hydration of concrete and results in stronger concrete surface strength is expected to correspond to a higher EI. To validate the utility of EI for assessing the quality of curing practices, concrete surface abrasion resistance tests were performed, and abrasion weight loss of specimens were obtained.

Moisture loss measurements could also provide a means to validate the utility of using EI to qualify the moisture retention capability of curing compounds. Regardless of the limitations of the standard ASTM test, it still provides an easy method of determining the water retention capability to represent the effectiveness of curing compounds. Generally, a better curing compound would lead to a lower moisture weight loss due to a better water retention capability. Accordingly, if a curing compound has a better water retention capability, the relative humidity under the filtered side of the curing plate (described in Chapter 3) is expected to be higher because of the greater moisture content yielding a higher EI. To validate the efficacy of using EI to represent the quality of curing practices in regards to the moisture retention capability, the moisture loss measurements were also made.

To start with, the relative humidity, moisture weight loss and surface abrasion weight loss measurements were taken on 0.4 w/c concrete specimens applied with three types of curing compounds at two different levels of application rate under no wind conditions. The detailed results are shown in Table A-1 in Appendix A. Plots of the abrasion weight loss results versus EI and the moisture loss measurements versus EI are shown in Figure 4-2 and Figure 4-3, respectively.

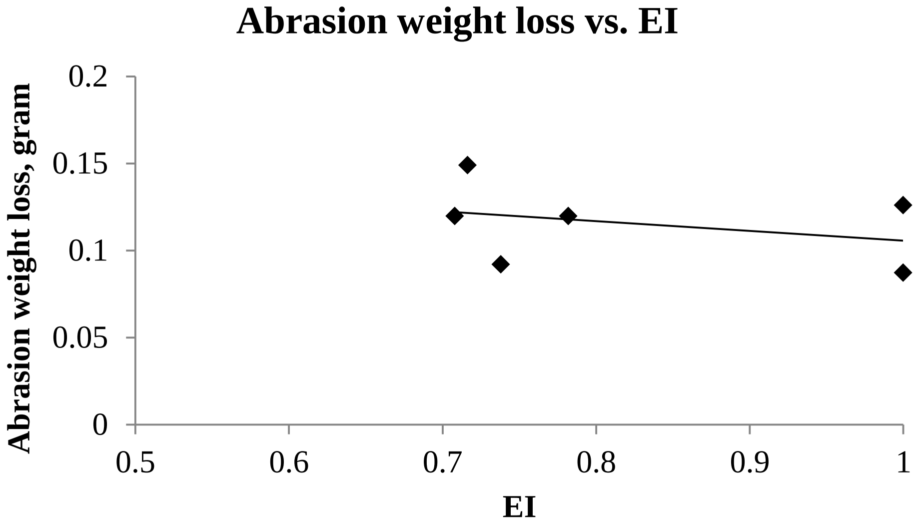

Figure 4-2 Abrasion weight loss vs. EI (w/c = 0.4)

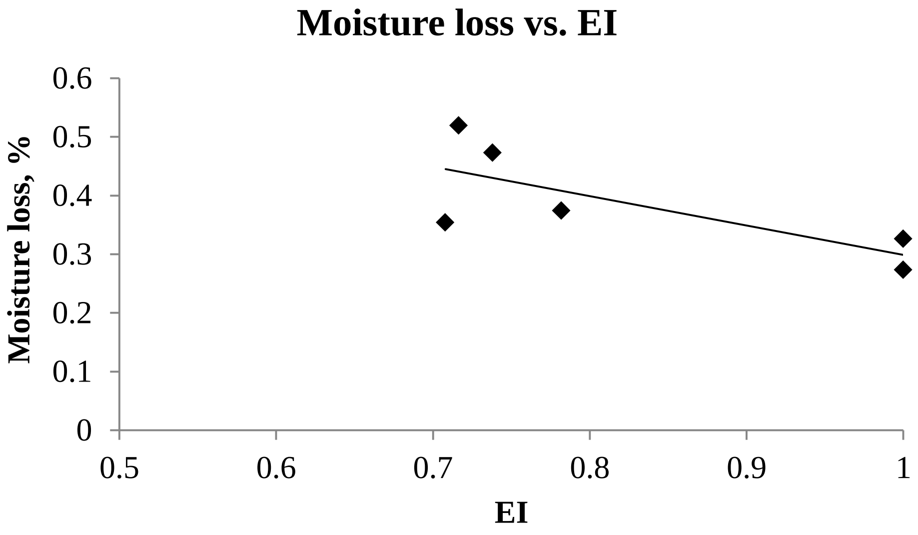

Figure 4-3 Moisture loss vs. EI (w/c = 0.4)

In order to determine the correlations of EI with abrasion weight loss and moisture loss measurements, a correlation analysis is conducted using the Pearson coefficient of correlation function. The statistical analysis is shown in Table 4-1.

Table 4-1 Correlation coefficients of EI with abrasion weight loss and moisture loss (w/c = 0.4)

	EI	Abrasion weight loss, gram	Moisture loss, %
EI	1		
Abrasion weight loss, gram	-0.339	1	
Moisture loss, %	-0.748	0.259	1

The correlation coefficient estimates the strength and the direction of the correlation between two variables, and it ranges from -1 to +1. If a correlation coefficient is greater than 0.8, it is considered as a strong correlation; whereas a correlation coefficient less than 0.5 would be considered as a weak correlation.

It is indicated in Table 4-1 that the correlation coefficient between EI and the moisture weight loss measurements is -0.748. This could be described as a moderate negative relationship, which meant that a high EI would correspond to a low moisture loss measurement. This relationship is as expected, because a higher EI is supposed to represent a better curing quality in terms of the moisture retention capability which leads to a lower moisture loss measurement of a concrete specimen.

As indicated in Table 4-1, the correlation coefficient between EI and the abrasion weight loss results is -0.339, which exhibits a weak negative relationship. The relationship could be described as a higher EI are associated with lower abrasion weight loss measurements. The results were as expected, however the relationship was considered weak.

During the conduct of abrasion resistance tests, it was observed that the results of the abrasion weight loss might be highly affected by the large randomly distributed aggregate particles. If some of the large aggregate particles happened to be at the surface of the tested area, the results of the abrasion weight loss might be significantly reduced considering the fact that the strength of the aggregate particles were likely greater than the strength of the concrete matrix. This factor may have biased the abrasion resistance of concrete mortar test results.

In order to mitigate the influence of the large aggregate particles, the gradation of the previous used sand was modified such that aggregate particles retained on No.8 testing sieve were removed from the mixture. As indicated by the gradation curves for the previous and modified sand gradations shown in Figure 4-4, none of the sand particles in the modified gradation were retained on the No.8 sieve size.

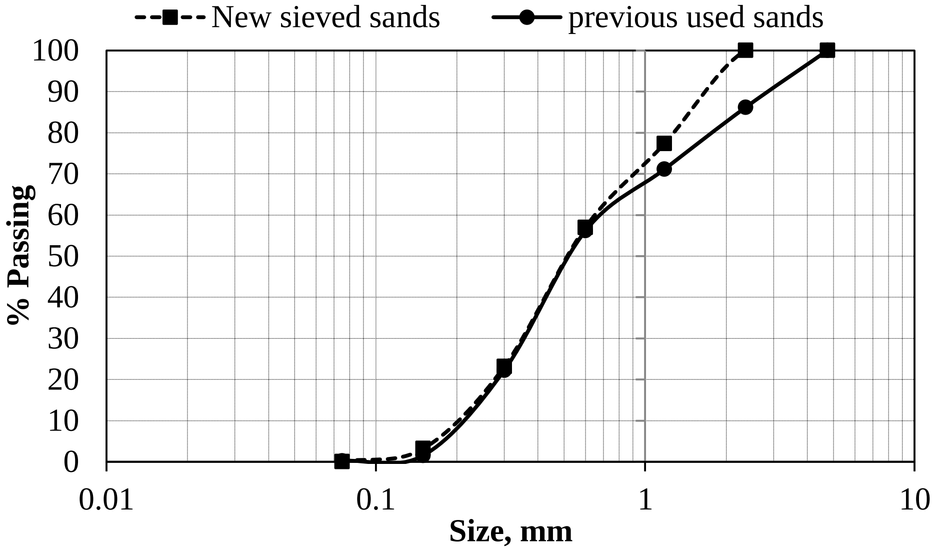

Figure 4-4 Gradation curves for previous and modified sand gradations

The modified sand gradation was used for the 0.43 w/c specimens in the test program. A table that contains EI, surface abrasion weight loss and moisture loss measurements of various curing practices is shown in Table A-2 in Appendix A. Plots of the abrasion weight loss results versus EI and moisture loss measurements versus EI are shown in Figure 4-5 and Figure 4-6, respectively.

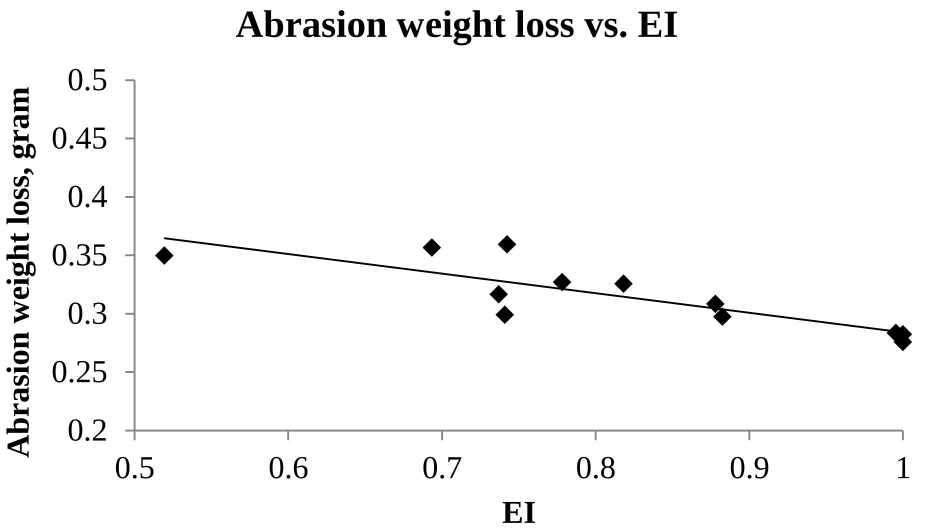

Figure 4-5 Abrasion weight loss vs. EI (w/c = 0.43)

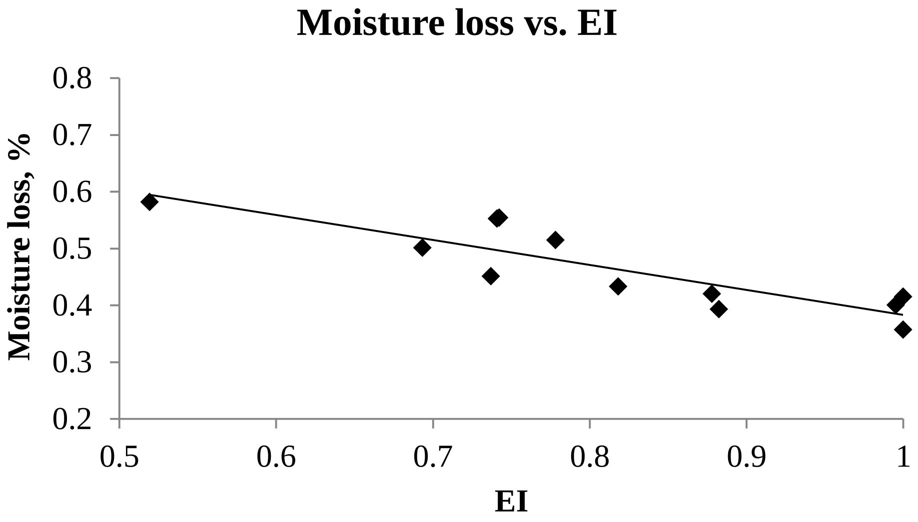

Figure 4-6 Moisture loss vs. EI (w/c = 0.43)

A correlation analysis is also conducted for the 0.43 w/c specimens to determine the correlation of EI with concrete surface abrasion resistance and moisture loss measurements using the Pearson coefficient of correlation function. The statistical analysis is shown in Table 4-2.

Table 4-2 Correlation coefficients of EI with abrasion weight loss and moisture loss (w/c = 0.43)

	EI	Abrasion weight loss, gram	Moisture loss, %
EI	1		
Abrasion weight loss, gram	-0.829	1	
Moisture loss, %	-0.864	0.753	1

As indicated in Table 4-2, the correlation coefficient between EI and abrasion weight loss and between EI and moisture loss is -0.829 and -0.864, respectively. A correlation coefficient of -0.8 generally means strong negative relationship. The plotted trends in Figure 4-5 and Figure 4-6 also showed the same clear phenomenon.

As indicated in Table 4-2 and Figure 4-5, EI showed a strong negative relationship with the abrasion weight loss results. This implied that a lower abrasion weight loss was strongly associated with a higher EI. This could be explained by the fact that a lower abrasion weight loss due to a stronger concrete surface abrasion resistance was believed to be the result of a better curing practice which improved the hydration process of concrete and increased the maturity of the concrete under the filtered side of the plate, therefore related to a higher EI. The statistical analysis justified the efficacy of using EI to represent the concrete curing effectiveness under the validation of the concrete surface abrasion resistance test results. Therefore, it is generally reasonable to conclude that a higher EI usually indicates a better curing practice.

The correlation analysis between EI and moisture loss measurements was conducted as shown in Table 4-2 and Figure 4-6. A strong negative correlation was also discovered between the two variables. The moisture loss measurements were made based the standard moisture retention test which considered that a lower moisture loss was generally related to a better quality of curing compound. For this study, it was observed that a lower moisture loss measurement was strongly related to a higher EI, which was considered to be the fact that a better quality of curing compound which had better moisture retention capability caused higher relative humidity under the filtered side of the plate, therefore corresponded to a higher EI. As a result, the efficacy of using EI to represent the quality of curing practices was testified and validated in terms of the moisture retention capability.

Some variations among the data shown in Figure 4-5 and Figure 4-6 were not entirely explained by the linear relationships. The sources of the variability could come from the temperature data collected by the ACMM system, the concrete surface abrasion resistance test results, the moisture loss measurements or the application of the curing compounds.

For the determination of EI, some of the discrepancies might be from the differences between the chilled mirror hygrometer sensors. Two devices of ACMM system are used in this research and each system consists of two sensors for measuring concrete surface temperatures which are used to determine relative humidity results as shown in Figure 3-1. Though the sensors are considered the most accurate type, minor differences still exist between the four sensors, which might have caused variance in the collected data. Based on the information provided by the manufacturer of the ACMM system, the accuracy of the temperature sensors is ± 0.2˚C. Nevertheless, the discrepancies that caused by the differences between the sensors are considered less significant.

Another source of uncertainties came from the abrasion resistance test results. To eliminate the influence, the sands were sieved, and the large aggregate particles retained on No.8 testing sieve were eliminated, all sands used for 0.43 w/c specimens were 100% passing through No.8 testing sieve. Nevertheless, the remaining aggregate particles may still have minor influence on the surface abrasion resistance test results. Second, the wear of the cutter heads used for surface abrasion resistance tests shown in Figure 3-6 may also account for the variability in results. Following the manufacturer’s instruction, the cutter heads were replaced approximated every 90 minutes of use. Because of the wear of the cutter heads, difference of sharpness exists between a new cutter head and a used one, which might have caused variability in the results. Third, the batch differences might also cause the difference in the measured abrasion weight loss of the specimens even under the use of same curing treatment and mixture proportion.

The causes of the variability within the moisture loss measurements could be from the influence of bleeding water. Bleeding water is a natural process that occurs at early concrete ages. Though each concrete specimen is consists of the same mixture proportioning, the amount of bleeding water may not be the same each time. If a curing compound is applied when bleeding is still occurring, it may result in the degradation of the curing quality. The determination of time of application to avoid the influence of bleeding water is always a concern in the practice of curing concrete.

The application of curing compounds may also affect the results. Because the application of curing compounds under the laboratory condition is done manually, the uniformity and the amount of the applied curing compounds may not be perfectly controlled, which may explain some of the discrepancies in the results.

4.2.2 Sensitivity Analysis of EI to Various Curing Treatments

To further validate the utility of using EI to represent the effectiveness of curing practices, sensitivity analyses are conducted for EI by comparing EI of various curing treatments, such as varying ambient wind conditions, types of curing compounds, application rate of curing compounds and the w/c of concrete mixture.

EI of different curing compounds under different wind conditions were tested and plotted as shown in Figure 4-7 and Figure 4-8. Figure 4-7 shows the EI for three types of curing compounds under both wind and no wind conditions at a 120 ft^2/gal application rate (AR). Figure 4-8 shows the EI for three types of curing compounds under both wind and no wind conditions at a 220 ft^2/gal application rate (AR). Wind condition is simulated at approximate 5 miles per hour by using an industrial fan.

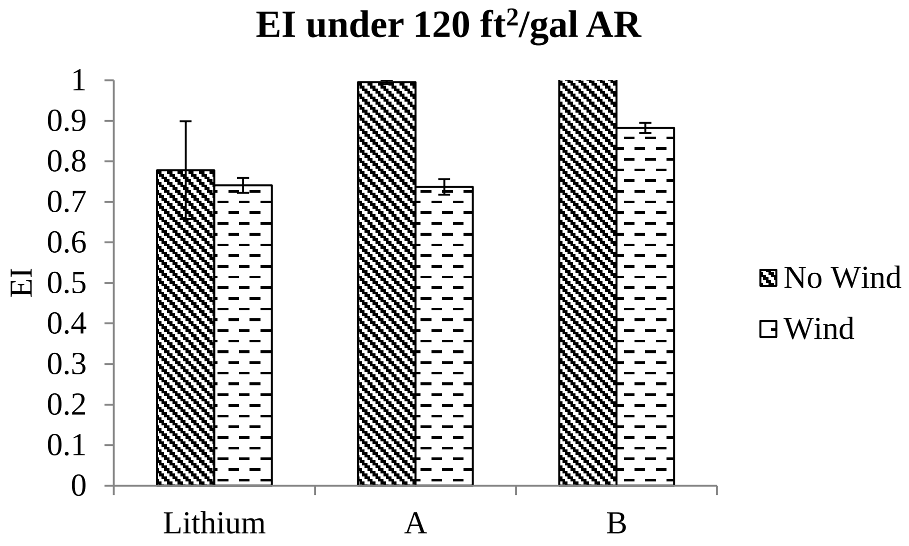

Figure 4-7 EI under 120 ft^2/gal application rate

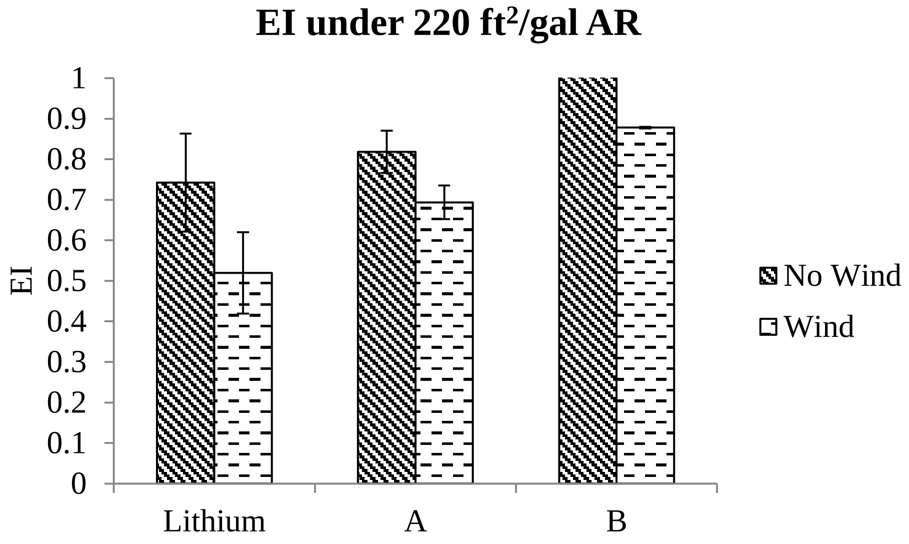

Figure 4-8 EI under 220 ft^2/gal application rate

The effect of wind condition on EI was investigated. It was observed from Figure 4-7 and Figure 4-8 that EI of curing compound A, B and lithium under no wind condition are consistently higher than EI under wind condition regardless of what the curing application rate was. This could be explained by the fact that the curing practices were substantially influenced by the ambient wind conditions which caused more moisture evaporation at the surface of concrete compared to specimens tested under no wind., Therefore a lower curing quality resulted which corresponding to a lower EI. However, some differences were observed in the test results. For instance, the difference of EI for lithium tested with and without wind was not very significant as shown in Figure 4-7. Reviewing the data sets shown in Figure 4-7 and Figure 4-8, it was found that the differences of EI for lithium cured specimens were much higher than specimens applied with the other curing compounds. Based on the observation of the lithium curing compound material, it was discovered that the consistency of lithium curing compound was lower than the other two types of curing compounds. It might be the inconsistency of the quality of the lithium curing compound that caused the variability in the data sets. Nevertheless, it was still considered that EI was very sensitive to the ambient wind condition. Expectedly, larger ambient wind condition causes higher moisture evaporation rate which results in lower EI.

Second, the sensitivity of EI to various types of curing compounds could also be observed from Figure 4-7 and Figure 4-8. For specimens applied with high application rate (120 ft^2/gal) of curing compounds shown in Figure 4-7, lithium showed remarkably lower EI compared with the other two curing compounds under no wind conditions. The difference of EI between curing compound A and B was very small, which was probably because that the 120 ft^2/gal application rate was so high that both curing compound A and B exhibited high quality of curing which made no difference in terms of EI under no wind condition. However, a significant difference between curing compound A and B was observed under wind conditions in Figure 4-7. This could be explained by that the wind condition accelerated the evaporation rate of the free moisture at the surface of concrete, thus resulted in lower curing quality compared with the environment without wind. In this circumstance, the presence of wind might have played a role of magnifying the quality difference between different types of curing compounds so that the quality difference of curing compounds dropped to a level that could be indicated by EI.

For specimens applied with low application rate (220 ft^2/gal) of curing compounds shown in Figure 4-8, significant differences of EI were shown for the three curing compounds under both wind and no wind conditions, where lithium had the lowest EI and curing compound B showed the highest EI. Comparing to the specimens applied with higher application rate (120 ft^2/gal) of curing compounds, the reason that the specimens applied with lower application rate (220 ft^2/gal) of curing compounds showed clear differences of EI for various curing compounds was probably because that the lowering of the application rate of curing compounds amplified the quality differences.. In general, EI was able to distinguish the quality differences between the three curing compounds. Especially for lithium and curing compound B, significant quality difference was observed in terms of EI; curing compound A had a moderate curing quality compared to lithium and curing compound B where it could exhibit similar curing quality as lithium or curing compound A in some certain circumstances. However, it is recommended that more tests should be performed to further validate the EI ranking of the curing compounds.

Third, in order to study the sensitivity of EI to various application rates of curing compounds, the results shown in Figure 4-7 and Figure 4-8 were re-plotted in Figure A-1 and Figure A-2 shown in Appendix A. It was discovered that for both lithium and curing compound A, EI at the higher application rate (120 ft^2/gal) was higher than the EI at the lower application rate (220 ft^2/gal) under both wind and no wind conditions. The observation that specimens applied with higher application rate of curing compounds exhibited higher EI was as expected, because a higher application rate of curing compounds yielded a better curing quality which corresponded to a higher EI. It was also found that for curing compound B, the EI at the higher application rate was almost the same as the EI at the lower application rate, regardless of what the wind condition was. This is probably due to the fact that curing compound B is one of the best curing compounds in the market, and the quality of curing compound B at a low application rate (220 ft^2/gal) was probably too high to be differentiated from the quality of B at a high application rate (220 ft^2/gal). EI might not be sensitive enough to assess the quality difference caused by the different application rates of such high quality curing compound even under wind conditions. However, this conclusion was drawn based this laboratory environment condition only. If the wind speed is greater than 5 miles per hour which happens quite often under field conditions, then EI might be able to perceive the subtle differences of the curing quality due to the change of application rate for such high quality curing compounds.

Fourth, the effect of changing w/c of specimens on EI was studied. 0.4 w/c specimens were applied with the three curing compounds under two different application rates under no wind conditions. Considering the scope of the study, application of curing compounds on 0.4 w/c specimens was not conducted under wind conditions. The results shown in Figure 4-9 and Figure 4-10 compare EI for specimens of 0.4 and 0.43 w/cs under no wind conditions.

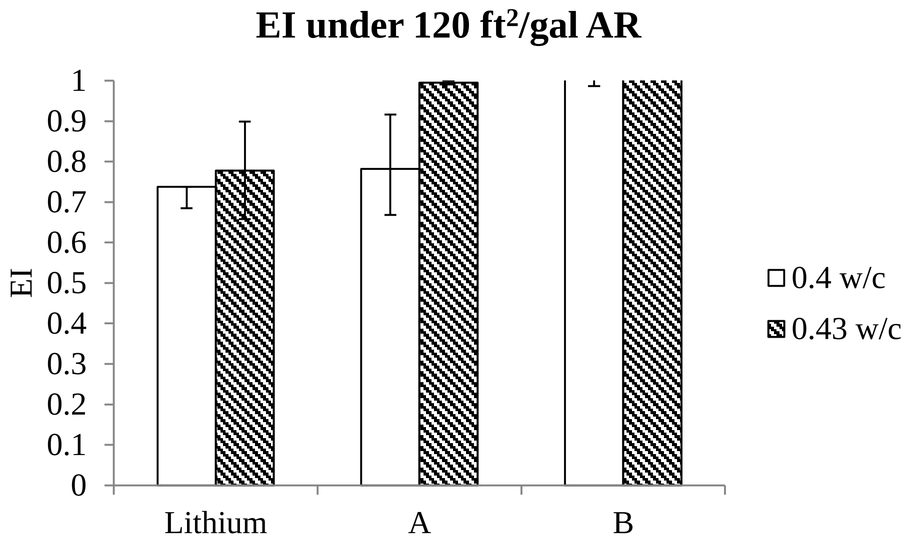

Figure 4-9 Comparison of EI for 0.4 w/c and 0.43 w/c specimens under 120 ft^2/gal application rate

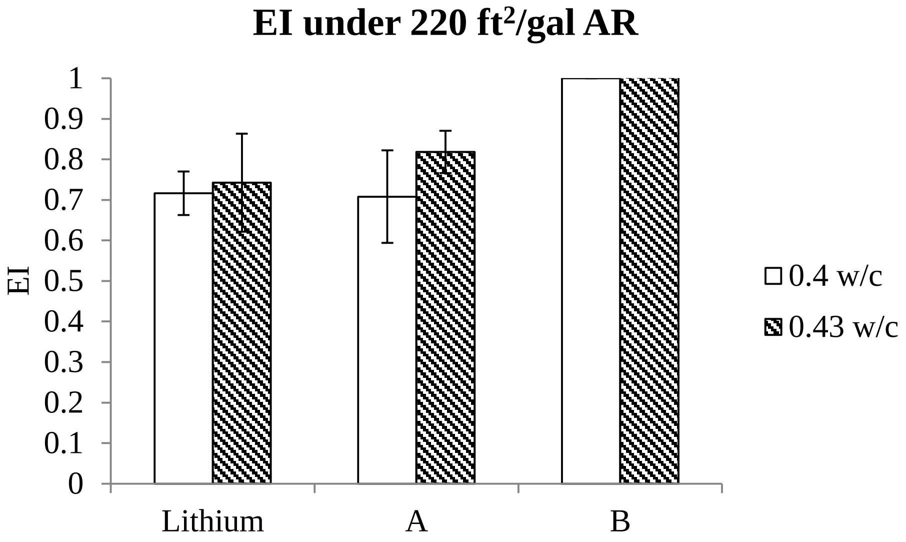

Figure 4-10 Comparison of EI for 0.4 w/c and 0.43 w/c specimens under 220 ft^2/gal application rate

As shown in Figure 4-9 and Figure 4-10, similar phenomenon were observed for specimens applied with lithium and curing compound A, where the 0.43 w/c specimens exhibited higher EI than 0.4 w/c specimens at both 120 ft^2/gal and 220 ft^2/gal application rates. The finding was as expected, because EI was a parameter that reflected the moisture condition at the concrete surface under the filtered plate. Higher w/c of specimens generally corresponded to higher free moisture content at concrete surface. In the same environment under the same curing practice, the amount of evaporated moisture was supposed to be theoretically identical for specimens with both 0.4 and 0.43 w/cs. Because 0.43 w/c specimens had more available free moisture, therefore more free moisture were remained after evaporation process and resulted in higher EI. For curing compound B, EI almost never changed regardless of what the w/c was and how much the curing compound was applied. This was probably because curing compound B had the best moisture retention capability; even the specimens were mixed at 0.4 w/c and were applied with only 220 ft^2/gal of curing compound B, the moisture conditions at the surface of concrete under the filtered side of the plate were still very high after 72 hours, which resulted in consistent high EI for specimens with both 0.4 and 0.43 w/cs.

4.3 Evaluation of Dielectric Constant (DC) Measurement

This section discusses the investigation of using DC measurements to evaluate the curing quality of concrete and the sensitivity analyses of DC measurements to various curing practices.

4.3.1 Background

It was discovered by researchers [39, 46, 47] that DC measurements were highly sensitive to the free moisture content in concrete, and a self-consistent model proposed by Lee [46] was used to estimate the volumetric free moisture content in concrete using the obtained DC measurements. This model verified that the DC measurements could be used to directly interpret the free moisture content changes in concrete. It was found that due to the high sensitivity of DC to the water content in concrete materials, measurements of DC showed strong relationships with the volumetric change of the unbound free water at the concrete surface. In general, it was found that high DC measurements that were associated with the early-age concrete corresponded to high volumetric moisture contents at the concrete surface. Due to moisture evaporation and hydration, the free water inside of concrete decreases with time. Accordingly, the measured DC showed decreasing trends with time. It was also indicated by Avelar [39] that the decreasing trends of DC measurements were influenced by curing environment, where well sealed specimens which were under a better curing condition exhibited lower decreasing rates of DC measurements comparing to specimens under exposed condition. This information provided promise of using DC measurements to differentiate curing quality for various curing compounds.

Because DC measurements are highly associated with moisture content at the surface of the concrete, and curing compounds affect the moisture condition of the surface concrete, the objective of the research considers the utility of DC measurements to distinguish the moisture retention capability for various curing compounds which are expected to moderate the moisture evaporation and maintain a humid condition at the surface of early-age concrete.

4.3.2 Sensitivity Analysis of DC Measurements to Various Curing Treatments

The summarized research findings of DC measurements made at the surface of 6-in diameter and 2-in height concrete specimens are described in this section. The DC measurements are used to represent the moisture retention capability of various curing practices. The sensitivity of DC measurements to various curing practices is also evaluated.

The DC measurements for specimens with 0.43 w/cs applied with different curing compounds are shown in Figure 4-11, Figure 4-12 and Figure 4-13.

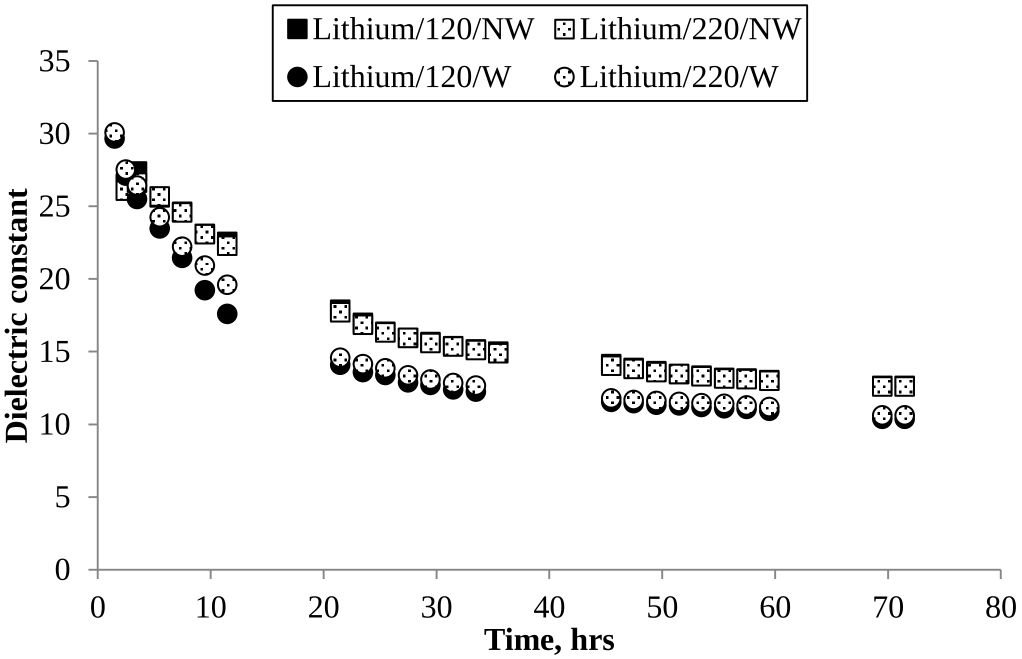

Figure 4-11 Dielectric constant for Lithium specimens (w/c = 0.43)[1]

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[1] The legend "Lithium/120/NW" showed in the figure means that the curing practice for the specimen is lithium curing compound at 120 ft^2/gal application rate under no wind conditions.

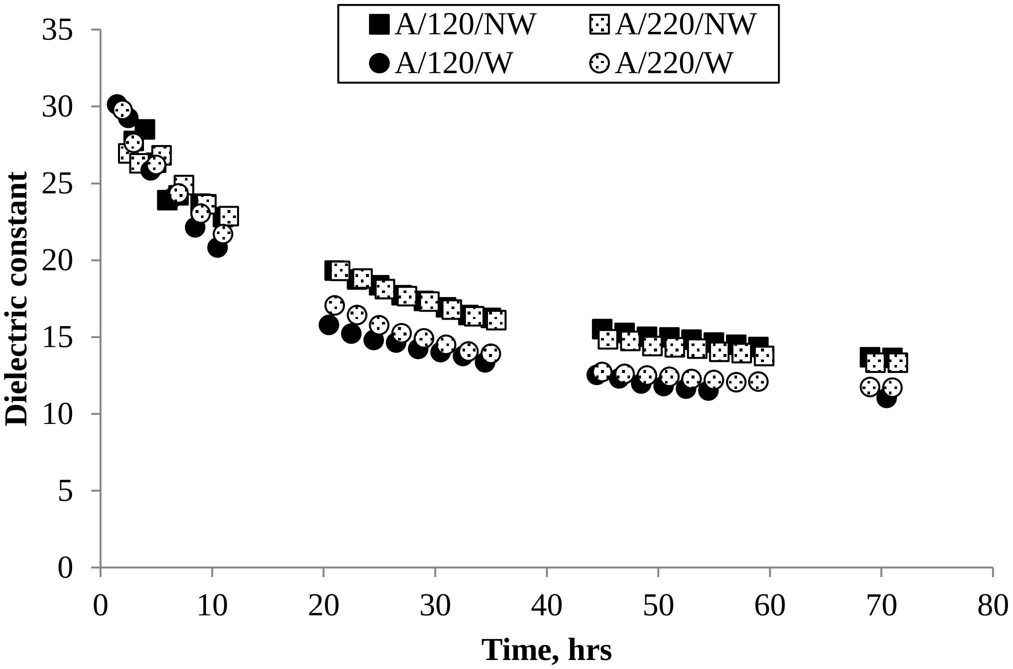

Figure 4-12 Dielectric constant for A specimens (w/c = 0.43)

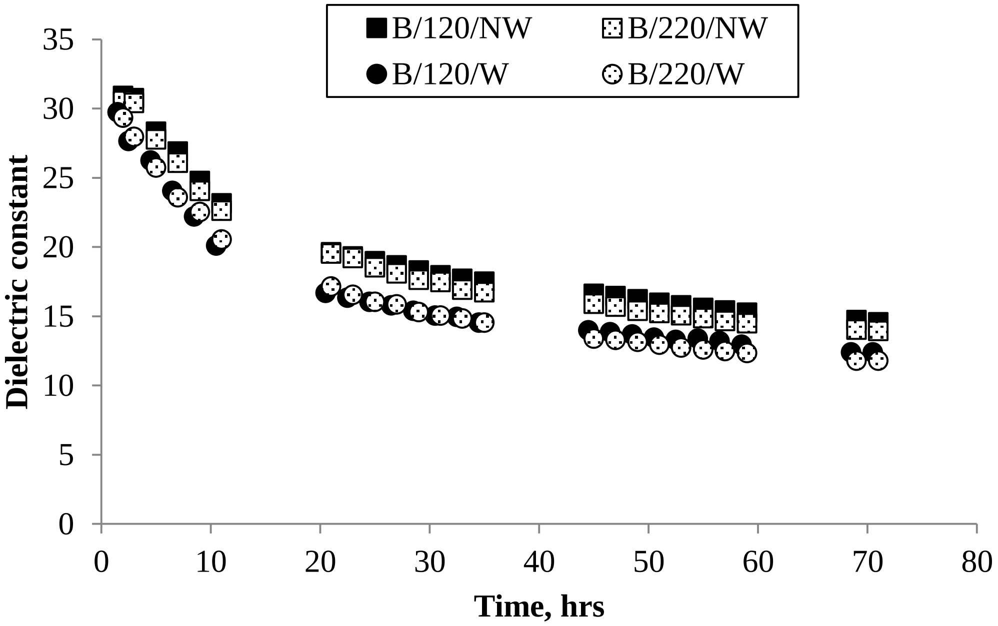

Figure 4-13 Dielectric constant for B specimens (w/c = 0.43)

From the three figures, it is seen that the DC measurements for specimens applied with three different curing compounds showed very similar sensitivity to wind conditions. Before the concrete set, the moisture content at the surface of concrete was very high; therefore higher DC measurements were shown at the first few hours. After that, DC measurements for all the specimens started to decrease. From approximately 20 to 72 hours, it was observed that for specimens with the same type of curing compound and application rate, the wind condition made significant differences on the DC measurements. DC measurements for specimens subjected to wind exhibited lower measurements than specimens tested under no wind conditions. As noted in the figures, it could be found that the decreasing rates of DC measurements after 20 hours for specimens treated with the same type and rate of curing compound under wind and no wind conditions were very similar. This might indicate that the differences of DC measurements after 20 hours between wind and no wind conditions were actually originated from the differences in the decreasing rates of DC measurements between wind and no wind conditions before 20 hours. A higher decreasing rate of DC at the first 20 hours resulted in lower DC later. This could be explained by accelerated evaporation rate at the surface of concrete during the early concrete hydration process due to the effect of wind. This apparently led to lower moisture content at surface of concrete which corresponded to lower DC measurements. It could be concluded that DC measurements were very sensitive to the ambient wind condition, which also verified that better curing conditions did lead to higher DC measurements because of better moisture retention capability.

The sensitivity of DC measurements to the application rate of curing compound could also be observed from Figure 4-11, Figure 4-12 and Figure 4-13. It is clear that for specimens with the same type of curing compound under the same ambient wind condition, the application rate made no significant difference for DC measurements. The decreasing trends for specimens applied with 120 ft^2/gal and 220 ft^2/gal application rates were almost identical. Although some of the trends showed minor differences between specimens applied with the two application rates of curing compounds, specimens applied with a rate of 120 ft^2/gal showed a little bit higher DC measurements over time than specimens applied with a rate of 220 ft^2/gal. This might suggest that the DC measurements were not sensitive to subtle quality differences caused by the rates of 120 ft^2/gal and 220 ft^2/gal under the current laboratory environment conditions. However, if tests are conducted under more severe moisture evaporation conditions, the DC measurements might exhibit more differences between different application rates.

To better understand the sensitivity of DC measurements to various types of curing compounds, Figures 4-11, 4-12 and 4-13 are re-plotted and shown in Figures A-3, A-4, A-5, and A-6 in Appendix A. The four figures show the comparisons of DC for the various curing practices. Regardless of the variability in the data sets during the first few hours after placement of concrete, which might be due to the high moisture content at the surface concrete during the initial stages, the decreasing trends of DC measurements showed significant differences between curing compound B and lithium after 20 hours. It was found that curing compound B had the lower decreasing rates of DC among the three curing compounds, whereas lithium showed the highest decreasing rates especially when the trends were compared from 10 to 35 hours. This could be explained by the fact that curing compound B had a better moisture retention capability than lithium, which resulted in higher moisture content and higher measurements of DC at the surface of concrete. The trends of DC measurements of curing compound A always fell between the trends of curing compound B and lithium, which was probably due to the fact that curing compound A had a moderate moisture retention capability compared with curing compound B and lithium. The levels of moisture retention capability for the three curing compounds indicated by DC measurements were consistent with the findings of using EI to assess the curing quality of curing compounds under various treatments in the previous section.

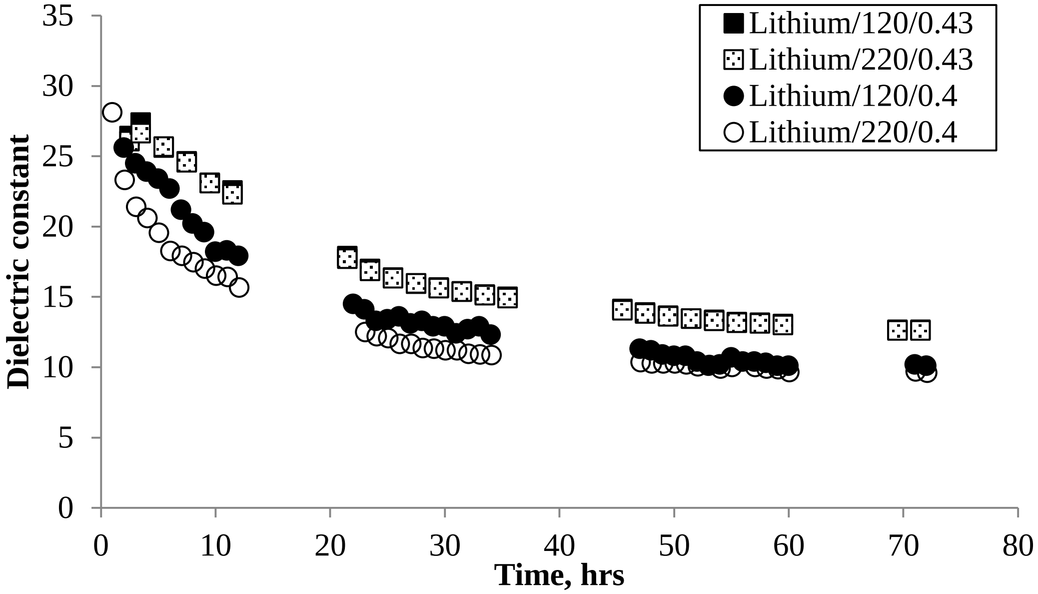

Figure 4-14 DC measurements for lithium specimens at 0.4 & 0.43 w/c

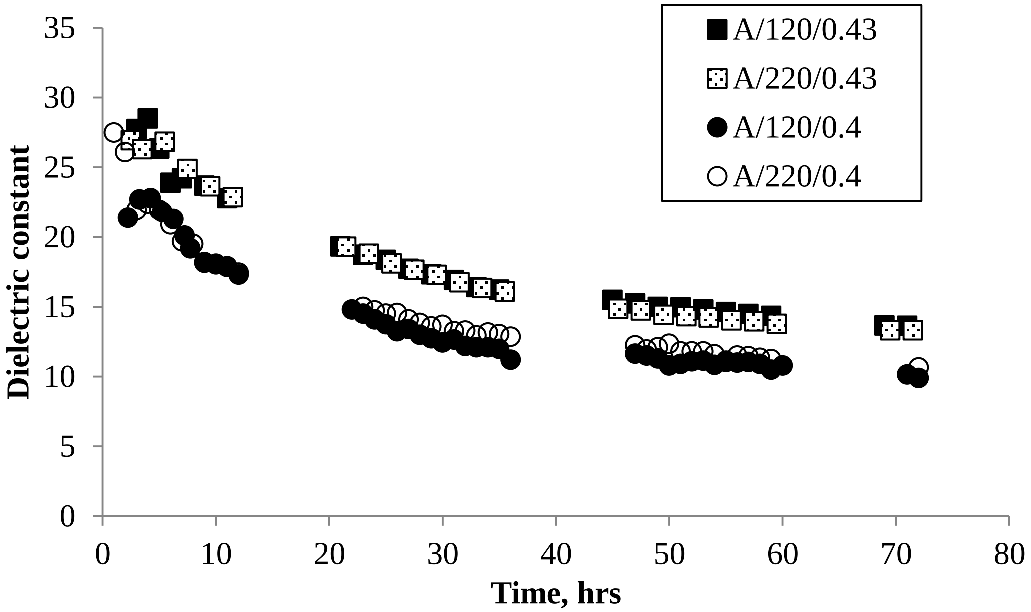

Figure 4-15 DC measurements for A specimens at 0.4 & 0.43 w/c

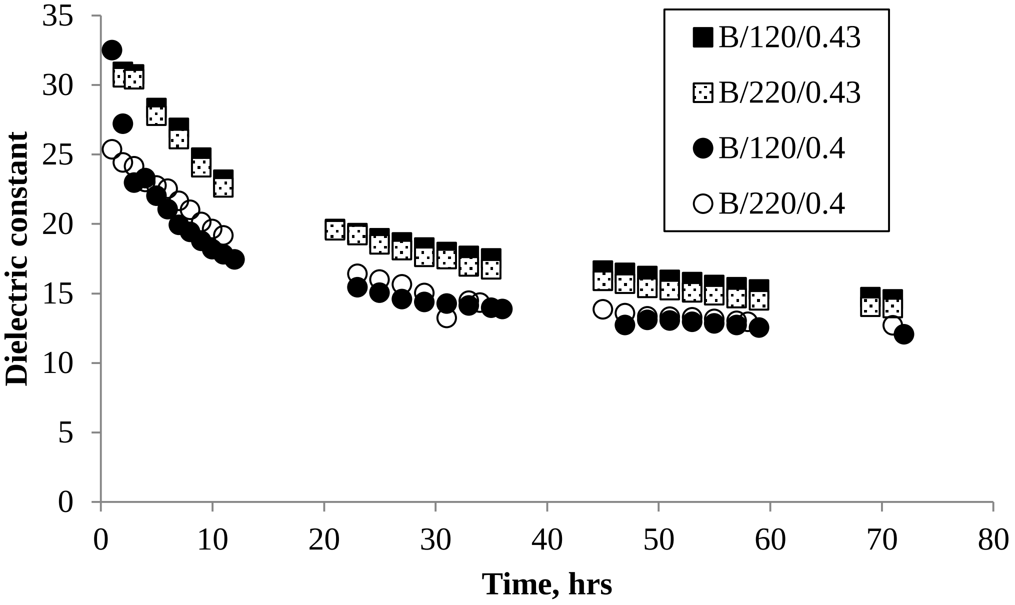

Figure 4-16 DC measurements for B specimens at 0.4 & 0.43 w/c

The DC measurements were also made for 0.4 w/c specimens applied with various curing practices. The comparison of DC measurements made on both 0.4 and 0.43 w/cs specimens was plotted as shown in Figure 4-14, 4-15 and 4-16.

As seen from the figures, clear differences of DC measurements were shown for specimens with different w/cs applied with the same curing compound at the same application rate. Compared to the DC measurements for 0.4 w/c specimens, the DC measurements of 0.43 w/c specimens were much higher. Comparing specimens applied with the same curing compound at the same application rate but with different w/cs, it could also be observed that the decreasing trends of DC measurements of specimens with the two w/cs were actually pretty similar from the beginning to the end of the measuring, though 0.43 w/c specimens started with higher DC measurements and 0.4 w/c specimens showed lower DC measurements at the beginning. The results were not surprising, because during the experiments, the curing compounds were actually applied at the surface of the thin layer of concrete mortar covered on top of the cap rather than directly sprayed at the concrete surface inside the cylindrical mold where DC measurements were taken. If the applied curing compound and the application rate were the same for a 0.43 w/c and a 0.4 w/c specimen, then the rate of moisture evaporation should be similar theoretically which was why the decreasing trends of DC measurements were similar between the specimens applied with the same type of curing practice. The difference between the DC of the 0.43 w/c and 0.4 w/c specimens comes from the difference in the w/c of the specimens, since higher volumetric water content dictates a higher DC of the 0.43 w/c specimens than the 0.40 w/c specimens. Therefore the 0.43 w/c specimens showed consistently higher DC measurements over time. The results indicate that even under the same curing practice, the DC measurements for concrete pavements with different mix proportions (i.e. the w/cs) might be quite different due to the initial difference in volumetric water content.

The sources of variability in the DC measurements may come from some of the following factors. First, the varied measurements may have something to do with the location of the measuring. To address this issue, the measuring location is confined by the 3-in diameter cylindrical mold as shown in Figure 3-9, which has just a little bit larger size than the size of the measuring probe. Second, the DC measurements depend on the operator to some extent. To reduce the human influence, only one person was conducting the measuring of DC most times, five data points were taken and an average value was obtained each time during measuring process. Third, some of the variability may come from the batch differences. This is almost unavoidable though the material and the mixing procedure were consistently well controlled.

5. FIELD INVESTIGATION AND VALIDATION

5.1 Background

Field investigation for evaluating the proposed protocol was conducted in a continuously-reinforced concrete pavement (CRCP) project in Victoria, TX. Due to the limitations of the ASTM C156 standard test, the described method of measuring moisture loss is not practical to perform on-site. The new protocol includes the ACMM system to measure relative humidity and temperature at the concrete surface to enable calculation of EI and the Percometer to measure DC at the concrete surface as a reflection of the moisture retention capability of the method of curing. The utility of the proposed new protocol was evaluated in terms of the field findings.

5.2 Testing Program

Considering the constraint on the amount of available measuring devices (only two ACMM systems were available), 4 sections were monitored by the ACMM system. The curing treatments for the four sections are shown in Table 5-1.

Table 5-1 Curing treatments for test sections

Test Section#	Shrinkage Reduction	Lithium Cure		Resin Cure	
		Type	Application rate	Type	Application rate
1	None	Transil	200 ft^2/gal	City White-E	200 ft^2/gal
2	None	Transil	200 ft^2/gal	City White-E	150 ft^2/gal
3	With	Sinak	200 ft^2/gal	City White-E	200 ft^2/gal
4	None	Sinak Mix	200 ft^2/gal	None	None

The shrinkage reduction admixture was used in the concrete mixture in Test Section #3 only. The purpose of using shrinkage reduction admixture was to reduce the potential of concrete chipping due to the stresses caused by concrete shrinkage. Lithium curing compound was sprayed at 200 ft^2/gal application rate after visible bleeding at concrete surface had subsided. Lithium curing compounds were all sprayed manually which might have caused uniformity issue to some extent. Once lithium was sprayed, the City White-E resin curing compound served as a second layer of coating was applied by using a spraying machine.

5.3 Investigation Approach

The field investigation approach was very similar to the methods used in laboratory. After pavement workers finished concrete surfacing operations, the top portion of the curing plate was placed on the surface of the concrete with a thin mortar layer on the filtered side of the plate as shown in Figure 5-1. This portion of the curing plate was put back and fixed on the base of the plate after application of the curing compound to create a bare spot on the pavement surface corresponding to the position of the curing plate. The operation of the ACMM system occurs over the rectangular bare concrete area which was covered by the curing plate and the supported ACMM system.

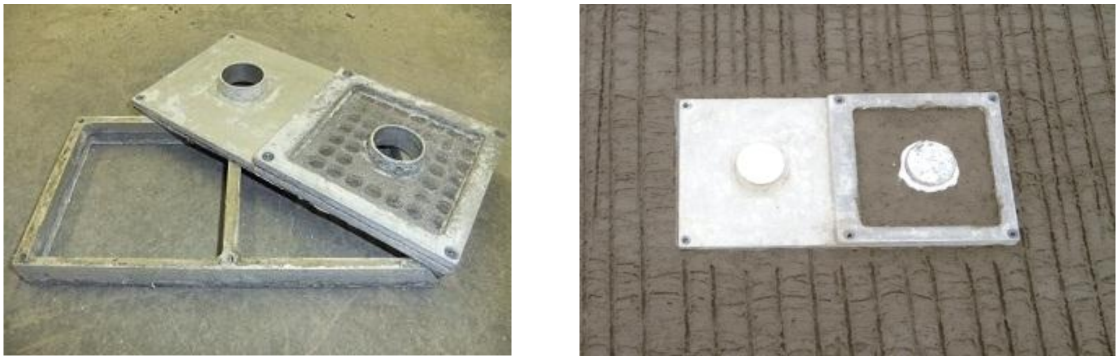

Figure 5-1 Curing plate Components and setup on a pavement surface

A plastic cylindrical mold was used for the DC measurements. As shown in Figure 5-2, the filtered top of the mold was covered by a thin concrete mortar layer before curing compounds were sprayed similar to that done with the filtered chamber of the curing plate. DC measurements provide a means to extend the curing compound effectiveness evaluation by the ACMM system over a wider area of paving rather than at a single position where the ACMM system is placed. For each section, two cylindrical molds were placed on different locations; one was placed near the ACMM system, the other one was placed approximate 20 feet away.

Figure 5-2 Cylindrical mold for DC measurements

After curing compounds were applied, the ACMM system was placed at the base location of the curing plate. The ACMM system as previously noted, records the ambient temperature, moisture and wind conditions. The top portion of the cylindrical mold was taken off the base portion when making DC measurements and was inserted back into the base tightly once the measurements were taken. Figure 5-3 shows the completed setup of the measuring devices.

Figure 5-3 Setup of the ACMM system and the mold for DC measuring

5.4 Research Findings

This section summarized the research findings of the field investigation for evaluating both the utilities of EI and DC measurements to assess the effectiveness of concrete curing compounds.

5.4.1 Evaluation of the Utility of EI

The measured relative humidity data and calculated EI for the four test sections are shown in Figures B-1 to B-4 in Appendix B. To compare the curing qualities for the four sections, the values of EI at a specific time of curing are extracted from the data plots shown in Appendix B. Due to the schedule conflicts and the limited available measuring devices, the relative humidity results for the first two sections were taken for approximately 43 hours before the ACMM systems were removed and installed on the other two sections for relative humidity and temperature data collection. Therefore, EI at 43 hours was determined from the data plots for the four sections as shown in Figure 5-4.

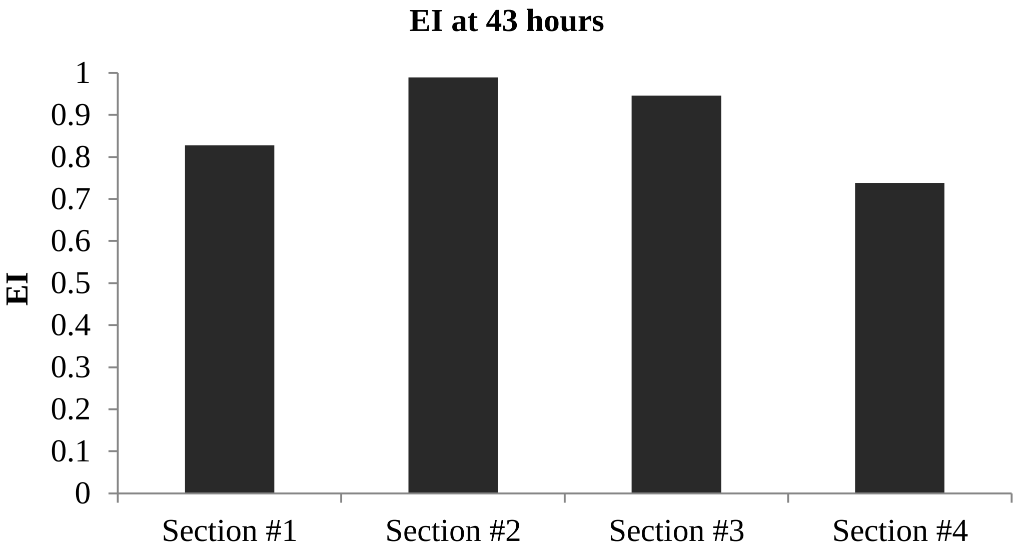

Figure 5-4 EI at 43 hours for four test sections

It is observed from Figure 5-4 that the ranking of the curing qualities for the four sections from highest to lowest is Section #2, Section # 3, Section #1 and Section #4.

When referring to Table 5-1 where the curing treatments are shown, the results of EI reasonably explained what the curing qualities of these sections are expected to be.

For Section #4, only “Sinak Mix” lithium curing compound was applied at 200 ft^2/gal application rate. Compared to a regular “Sinak” lithium curing compound which was used in Section #3, though “Sinak Mix” was considered by the manufacturer to have better curing quality because of the resin mixed inside, however, Section #4 was only sprayed with one layer of the curing compound coating compared with the other three sections. Lacking the application of the high quality resin curing compounds that were sprayed as a second layer of coating for the other three sections was the main reason to account for the low quality of curing and EI on Section #4, though “Sinak Mix” was considered a better lithium curing compound than “Sinak” as the first lithium layer of curing compound.

Section #2 exhibited the highest EI which was mainly due to the fact that Section #2 was sprayed with a higher application rate (150 ft^2/gal) of resin curing compounds than Section #1 and Section #3. Comparing Section #1 with Section #3, the application rate for both lithium and resin curing compounds and the type of the resin curing compound were the same, therefore the difference of EI for the two sections might be attributed to the following two reasons. First, it might come from the quality difference between “Transil” and “Sinak” Lithium that were applied for Section #1 and Section #3. “Sinak” lithium sprayed on Section #3 might have a better quality than the “Transil” lithium sprayed on Section #1, which caused higher EI on Section #3 than Section #1. Second, the uniformity of the curing compound might cause the difference of the curing quality. The “Transil” lithium and resin curing compounds on Section #1 were both sprayed manually; on Section #3, the “Sinak” lithium was sprayed manually, but the resin curing compound was sprayed by a spraying machine which provided better uniformity of curing compound coverage. The machine sprayed resin curing compound on Section #3 had a better uniformity than the manually sprayed resin curing compound on Section #1, which resulted in better curing performance and was reflected by EI.

5.4.2 Evaluation of the Utility of DC measurements

DC measurements were also taken for the four sections over a 43 hour period. The detailed results are shown in Figure B-5 in Appendix B for the four sections. Though five data points were taken for each time and averaged, the results showed higher variability and inconsistency under the field conditions, which might be caused by the inconsistent measuring process involved by three people who took shifts over the measurement period.

In order to better understand the character of the DC measurements, a modified Weibull distribution function shown in Equation 5-1 was used to generate regression curves for the DC measurements. The fitted regression curves for the four sections are shown in Figure 5-5. The fitted regression parameters of the four sections are shown in Table 5-2.

$$w(t, \alpha, \beta, \tau) = \tau.[1 - e^{-(\frac{1}{t.\beta})^{\alpha}}] \tag{5-1}$$

Where:

t = elapsed time, hours

τ = amplifying parameter

β = scaling parameter, and

α = shift parameter

Table 5-2 Regression parameters and EI for the four test sections

Test Section#	***α***	***β***	***τ***	**EI**
1	0.295	0.091	13.869	0.828
2	0.472	0.064	12.551	0.989
3	0.712	0.055	16.474	0.946
4	0.293	0.206	16.674	0.738

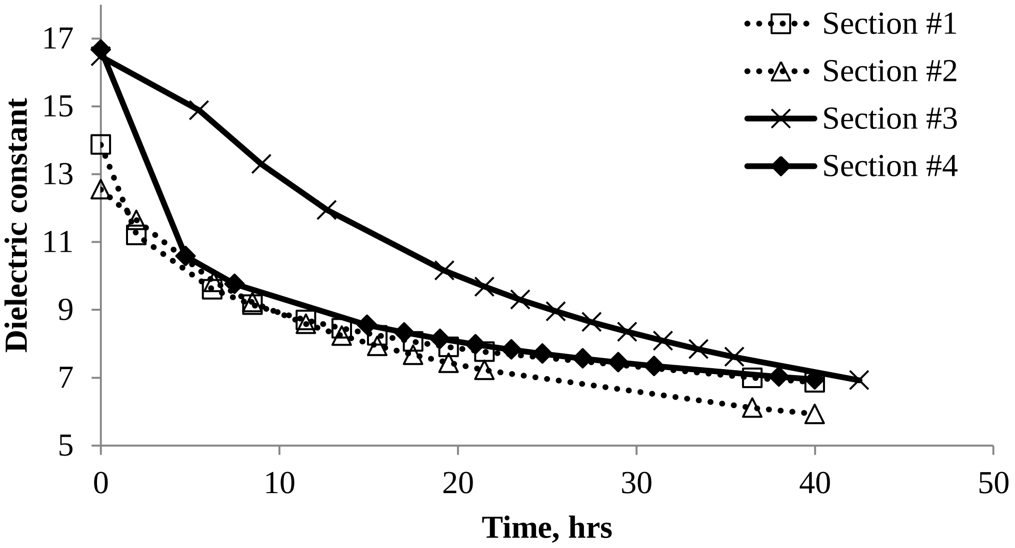

Figure 5-5 Regression curves for DC measurements

Section #1 and Section #2 were constructed two days before the construction of Section #3 and Section #4. It was observed that the concrete mixtures were a bit different in the workability. The mixtures of Section #1 and #2 were not as workable as the mixtures of Section #3 and #4, where some difficulties were experienced in the paving process. This indicated that the free water contents in the mixtures of Section #1 and #2 might have been lower than the free moisture contents in Section #3 and #4, which may account for the observations made from Figure 5-5 that the very initial DC measurements for Section #3 and #4 were quite higher than the initial DC measurements for Section #1 and #2.

As observed from Figure 5-5, the decreasing trends of Section #1 and #2 are very similar during the first 15 hours, but are offset afterwards. Because the two trends started at different positions, comparison of them from Figure 5-5 is not easily distinguishable. Based on the regression parameters shown in Table 5-2, it is found that the regression parameter beta which represents the decreasing rate for Section #2 is lower than the beta for Section #1. This could indicate that the curing practice applied on Section #2 had a better quality and moisture retention capability which resulted in a lower rate of the concrete surface moisture evaporation and corresponded to lower decreasing rate of DC measurements. Because two DC measuring molds were set up for Section #1 and Section #2, the standard deviation for the sections were calculated. The standard deviation is 0.0015 for Section #1, and is 0.023 for Section #2.

Comparing the DC measurements for Section #3 and #4, a huge difference was found between the two trends for the first 10 hours, where DC measurements for Section #4 showed much higher decreasing rate than that of Section #3. Also, the regression parameter beta of Section #3 was much smaller than the beta of Section #4. Both the observations indicated that the qualities of the applied curing practices for these two sections were significantly distinct and the curing practice applied for Section #3 might be much better than the practice applied for Section #4. Referring to Table 5-1, it was further validated that Section #3 did have a much better curing practice than Section #4 considering the fact that an additional layer of resin curing compound was sprayed on Section #3 which significantly improved the curing quality compared to the curing practice applied for Section #4 where only one layer of lithium curing compound was applied.

Results of regression parameter beta and EI for the four test sections are shown in Figure 5-6.

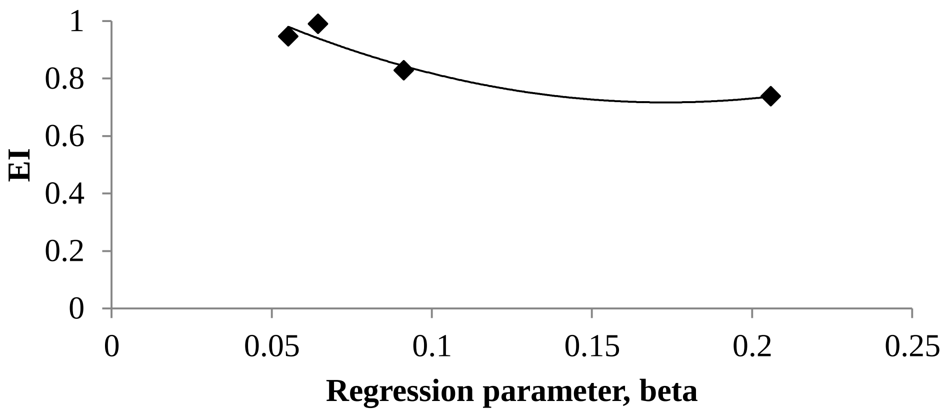

Figure 5-6 EI vs. Beta

As shown in Figure 5-6, a direct relationship was found between EI and regression parameters of beta. A higher EI is generally associated with a lower beta which represents a lower decreasing rate of DC measurements and a better moisture retention capability of the curing practice. Therefore, the utility of using DC measurements to qualify curing practices are validated. Though more results are needed to further understand the relationship between EI and beta, it still shows good potential for using beta and DC measurements to extend the evaluation of the effectiveness of curing compounds beyond the use of EI.

5.5 Application of the New Protocol

As indicated in the last section, a relationship between beta and EI was found for the four test sections where both the ACMM systems and the molds for DC measuring were set up. If one wants to know the EI for more pavement sections, the ACMM systems will not be available because of the limited amount of the devices. However, DC measurements for more test sections can be easily taken by setting up the measuring molds. Once DC measurements are taken and the beta is derived from the DC measurements for a specific test section where ACMM system is not available, the EI for this section could be predicted based on the known relationship between EI and beta as shown in Figure 5-6, though the relationship is valid for this field investigation only considering the fact that the ambient environment condition is different for a different construction project.

One of the applications of the new protocol is that the EI could be used to relate with the future performance of the concrete pavement sections, in order to further investigate how the performance of the newly paved concrete pavement is affected by the various curing practices. The EI of the test sections are determined either from calculating the relative humidity and temperature data obtained by the ACMM system or using the relationship between EI and beta once DC measurements are taken. EI is a concise measure that represents both the moisture retention condition and the strength development of the concrete pavement. Therefore,

Another application of the new protocol is that the results of beta and EI could be used to predict the application rate of curing compounds for a new construction project with a known ambient environment condition.

The potential of evaporation rate for a given ambient environment condition is calculated in Equation 5-2,

$$PE = (70^{2.5} - (\frac{\mathrm{RH}}{100} * \mathrm{T}^{2.5}) * (1 + 0.4 * \mathrm{WV}) * 0.000001 \qquad (5\text{-}2)$$

Where:

PE = potential of evaporation rate, lbs./ft^2/hrs.
RH = the relative humidity of ambient conditions, %
T = the temperature of ambient conditions, ˚F
WV = the wind velocity of ambient conditions, mph

As indicated in Figure 5-6, EI and beta have a certain relationship under the ambient environment condition in the Victoria project. In this project, Section #1 and #2 were paved under the same ambient environment (they were paved at the same day which is different from Section #3 and #4) and were applied with the same types of curing compounds (the only difference was that Section #1 was applied with 200 ft^2/gal of resin cure and Section #2 was applied with 150 ft^2/gal of resin cure as shown in Table 5-1). Using PE 1 to represent the ambient condition for Section #1 and Section #2, the EI vs. beta for the two sections is plotted in Figure 5-7. Based on the curve of PE 1, the relationship between EI and beta are extrapolated to multiple ambient environment conditions which are represented by different PEs (PE 2 and PE 3). The relationships between EI and beta for multiple ambient conditions are shown in Figure 5-7.

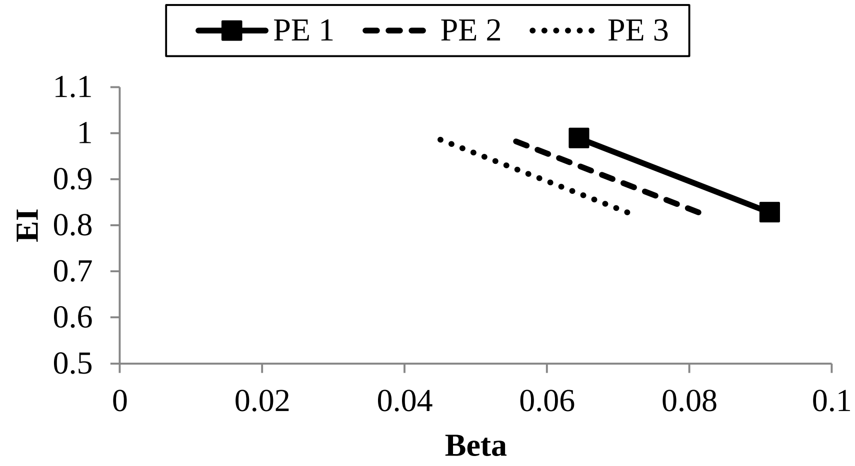

Figure 5-7 EI vs. Beta for different PEs

Beta under field conditions is affected by the potential of evaporation rate (PE) of the ambient conditions and the application rate of the curing compound. The relationship between beta and the application rate of a single curing compound under different PEs could be plotted as shown in Figure 5-8. In Figure 5-8, PE 1 shows the relationship between beta and the application rates of the resin cure applied at Section #1 and #2, and curves of PE 2 and PE 3 are the extrapolations of this relationship under different ambient conditions.

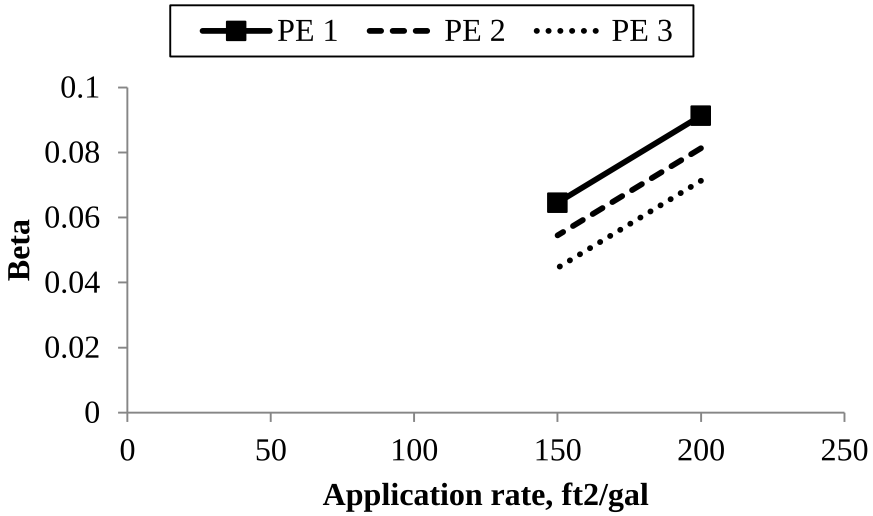

Figure 5-8 Beta vs. Application rate for different PEs

Both Figures in 5-7 and 5-8 show the empirical results of many field investigations (some of them will be conducted in the future) where the same type of curing compound (resin cure is shown here as an example) was applied at different application rates under different PEs. Once the relationships are established, one could predict the best application rate of a curing compound under a given PE for a new construction project.

By knowing the PE of the construction project, one can determine the beta from Figure 5-7 to meet a designed EI; once the beta is determined, the application rate of the curing compound could be determined from Figure 5-8 under the given PE. It provides an empirical method to predict the application rate of a curing compound for a given ambient environment condition of a new construction project.

6. CONCLUSIONS

The application of liquid membrane-forming compounds is one of the most widely used methods to moderate the early-age concrete surface moisture loss. The present standard test has some intrinsic limitations for evaluating the quality of curing compounds, especially for its inapplicability under field conditions. The new proposed protocol considers of using nondestructive methods to evaluate the effectiveness of curing practices and is versatile under both laboratory and field conditions.

Under the laboratory condition, the new protocol consists of measuring relative humidity and temperature of the curing affected concrete surface for calculating an effectiveness index (EI) to assess the effectiveness of curing compounds. Additionally, moisture loss measurements were also taken and were found to have significant relationship with EI, where specimens with higher EI related to lower moisture loss measurements, which corresponded to better moisture retention capability and curing effectiveness. Surface abrasion resistance tests were also conducted at concrete surface. The measured surface abrasion weight loss results were also found to have remarkable correlation with EI after the sands were refined to eliminate variance. It was discovered that higher EI were generally associated with lower abrasion weight loss which corresponded to higher concrete surface abrasion resistance caused by better curing practices. EI was also found to be affected by ambient wind conditions where the amplifying effect of wind conditions made EI more sensitive to capture the quality difference of different curing practices. EI was also able to distinguish the quality differences of curing compounds due to the different types and application rates. However, for very high quality curing compounds, EI was not sensitive enough to exhibit the curing quality difference caused by changing application rate of the curing compound which might be due to the fact that the high quality curing compounds had very effective curing quality even at lower levels of application rates. For specimens with different w/cs, EI was also able to distinguish the relative humidity differences induced by the different water contents within mixtures.

The dielectric constant (DC) measurements were also conducted for concrete specimens under laboratory conditions as an indicator for free moisture content at the surface of concrete and were related to the moisture retention capability of curing compounds. The DC measurements were found to distinguish the quality differences of the curing compounds under different ambient wind conditions for specimens with different w/cs. However, changing application rates of curing compounds did not significantly effect on the DC measurements.

The utility of the new protocol was investigated and validated under the field conditions in the concrete pavement construction project in Victoria, TX where both EI and DC measurements were taken. The results of EI showed significant utility for assessing the effectiveness of the curing practices in terms of the types and the application rates of the applied curing compounds. The results of EI were in accordance with the expectation of the curing practices applied for the test sections. DC measurements were also taken and regression curves were made based on a modified Weibull distribution function. Regression parameter beta related to decreasing rate of the DC measurements for the test sections showed promises for predicting the effectiveness of curing compounds regarding the moisture retention capability. EI were also found to have a certain relationship with the regression parameter beta. By using the relationship and the measured DC, EI could be predicted based on the beta for many pavement sections where the ACMM system is not set up.

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APPENDIX A – LABORATORY EXPERIMENT DATA

Table A-1 EI, abrasion weight loss and moisture loss results (w/c = 0.4)

Type	Application rate, ft^2/gal	Wind condition	EI	Abrasion Weight Loss, gram	Moisture Loss, %
Lithium	120	No Wind	0.738	0.092	0.473
Lithium	220	No Wind	0.717	0.149	0.520
A	120	No Wind	0.782	0.120	0.374
A	220	No Wind	0.708	0.120	0.354
B	120	No Wind	1	0.126	0.273
B	220	No Wind	1	0.087	0.326

Table A-2 EI, abrasion weight loss and moisture loss results (w/c = 0.43)

Type	Application rate, ft^2/gal	Wind condition	EI	Abrasion Weight Loss, gram	Moisture Loss, %
Lithium	120	No Wind	0.778	0.327	0.514
Lithium	220	No Wind	0.742	0.359	0.554
Lithium	120	Wind	0.741	0.299	0.552
Lithium	220	Wind	0.520	0.350	0.582
A	120	No Wind	0.995	0.284	0.401
A	220	No Wind	0.818	0.326	0.433
A	120	Wind	0.737	0.317	0.451
A	220	Wind	0.694	0.357	0.501
B	120	No Wind	1.000	0.276	0.357
B	220	No Wind	1.000	0.282	0.415
B	120	Wind	0.883	0.298	0.393
B	220	Wind	0.878	0.308	0.420

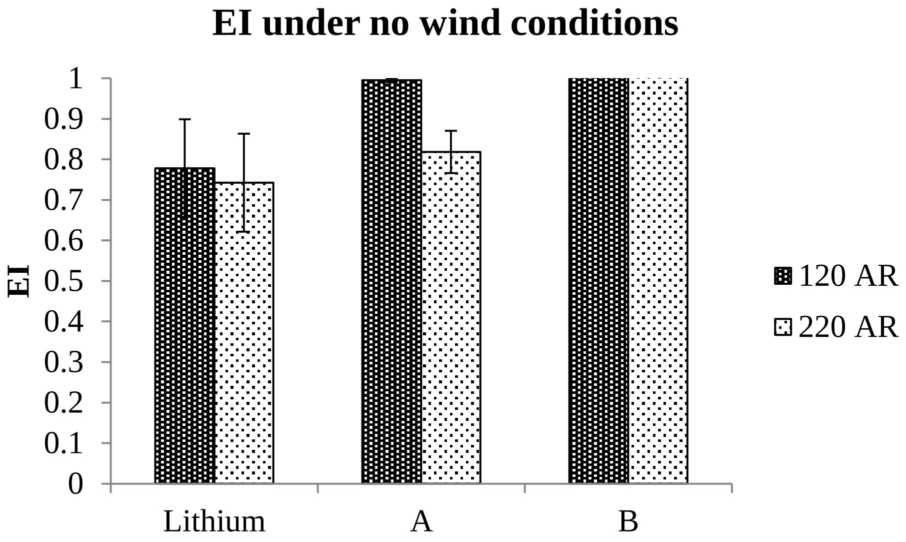

Figure A-1 EI under no wind conditions (w/c = 0.43)

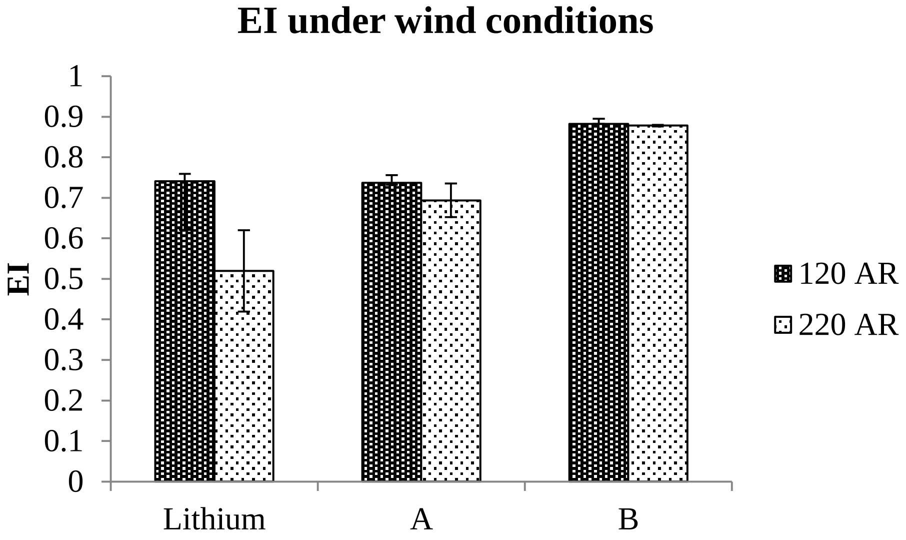

Figure A-2 EI under wind conditions (w/c = 0.43)

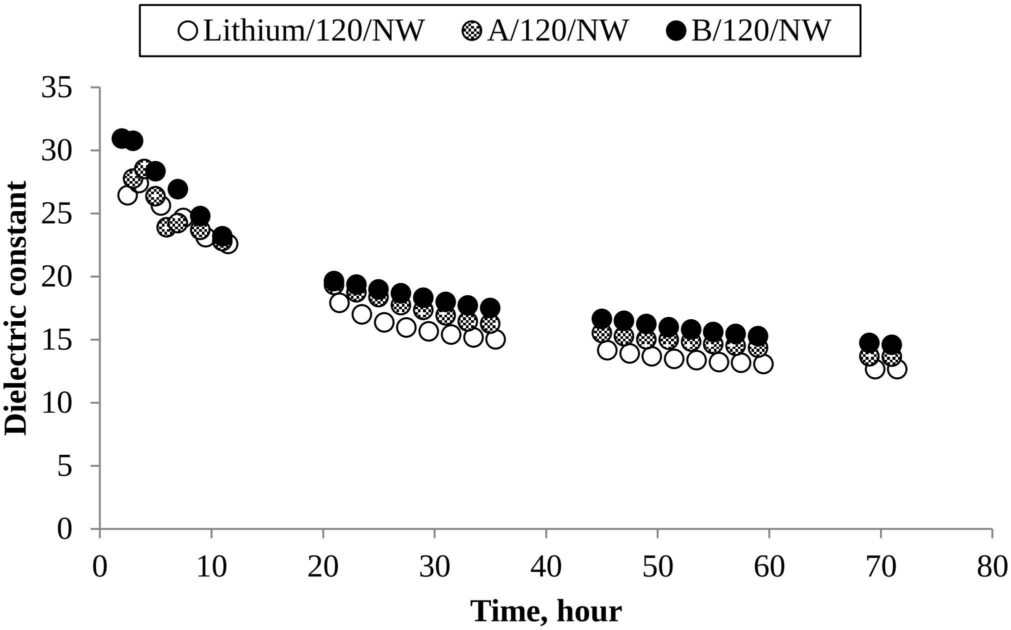

Figure A-3 DC measurements for specimens applied with 120 ft^2/gal of curing compounds under no wind conditions

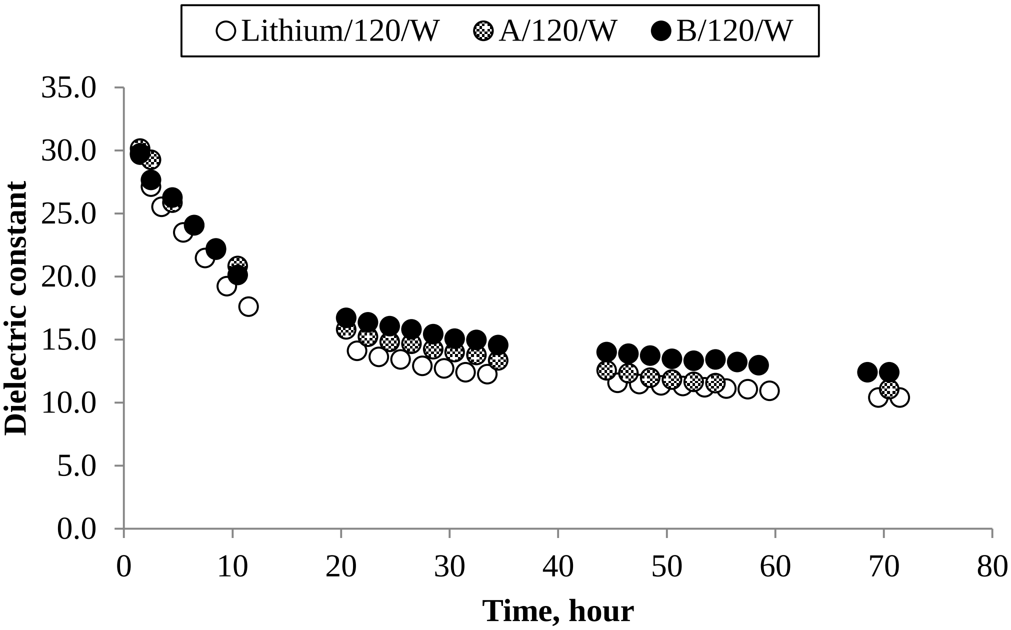

Figure A-4 DC measurements for specimens applied with 120 ft^2/gal of curing compounds under wind conditions

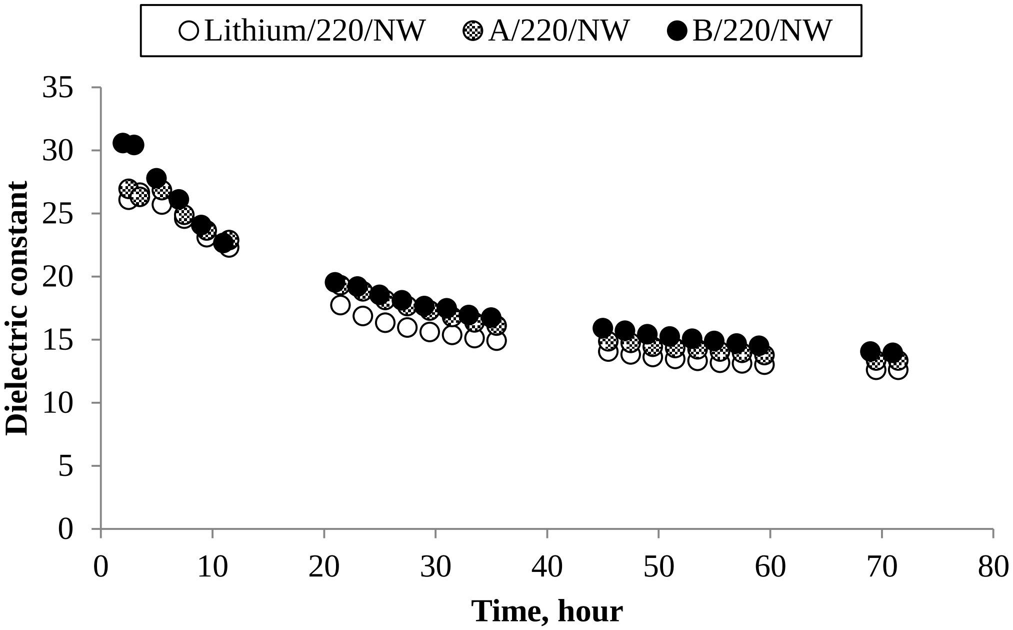

Figure A-5 DC measurements for specimens applied with 220 ft^2/gal of curing compounds under no wind conditions

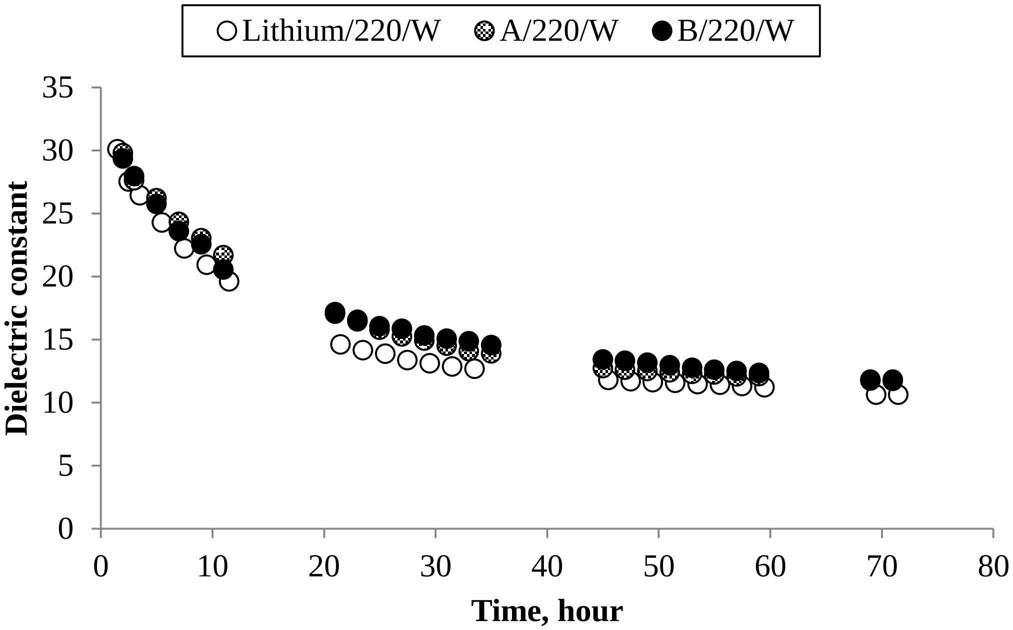

Figure A-6 DC measurements for specimens applied with 220 ft^2/gal of curing compounds under wind conditions

APPENDIX B – FIELD EXPERIMENT DATA

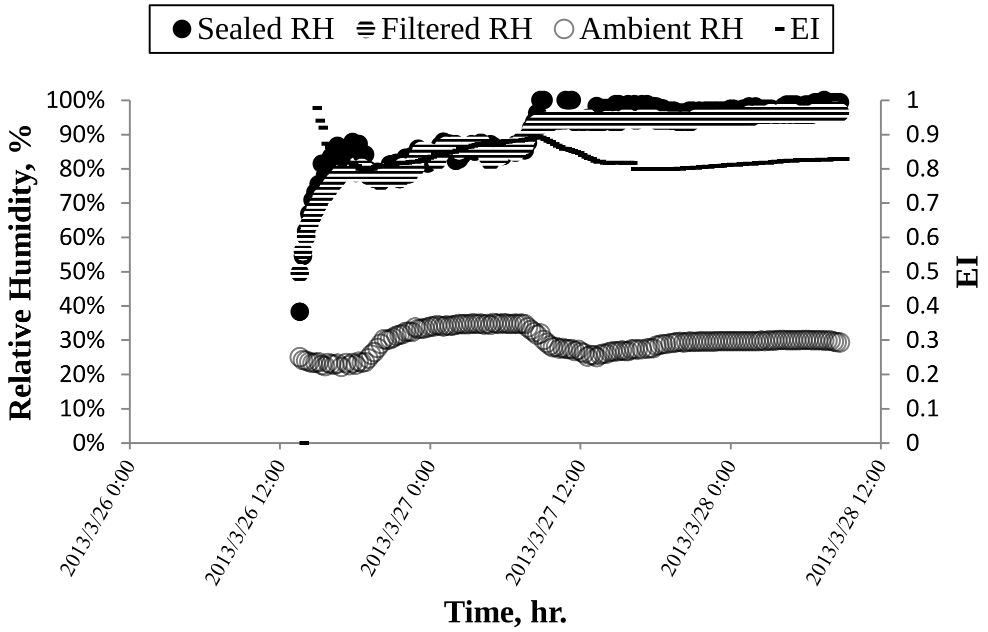

Figure B-1 Relative Humidity data for Section #1

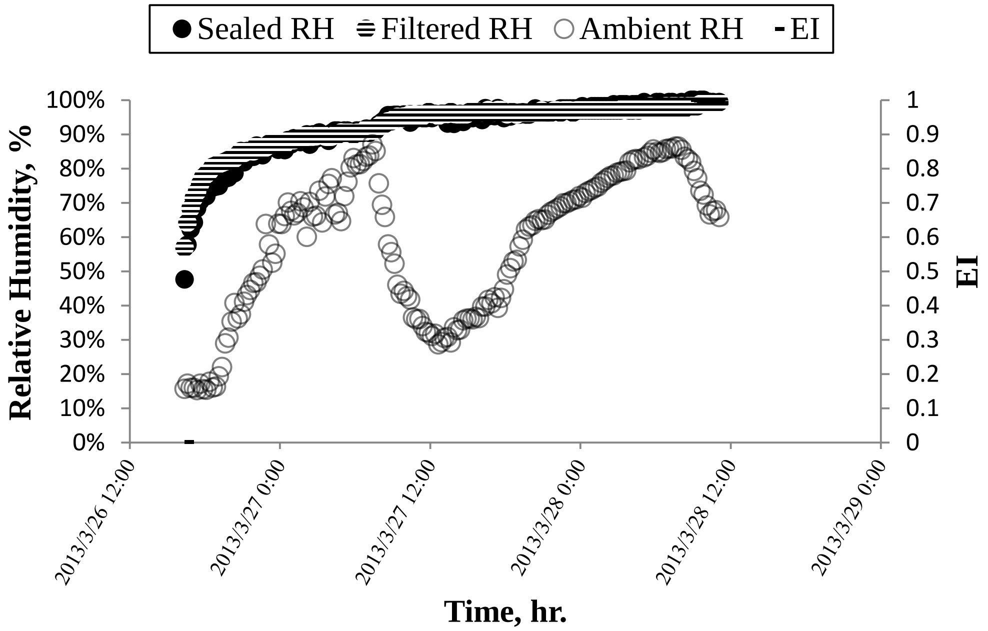

Figure B-2 Relative Humidity data for Section #2

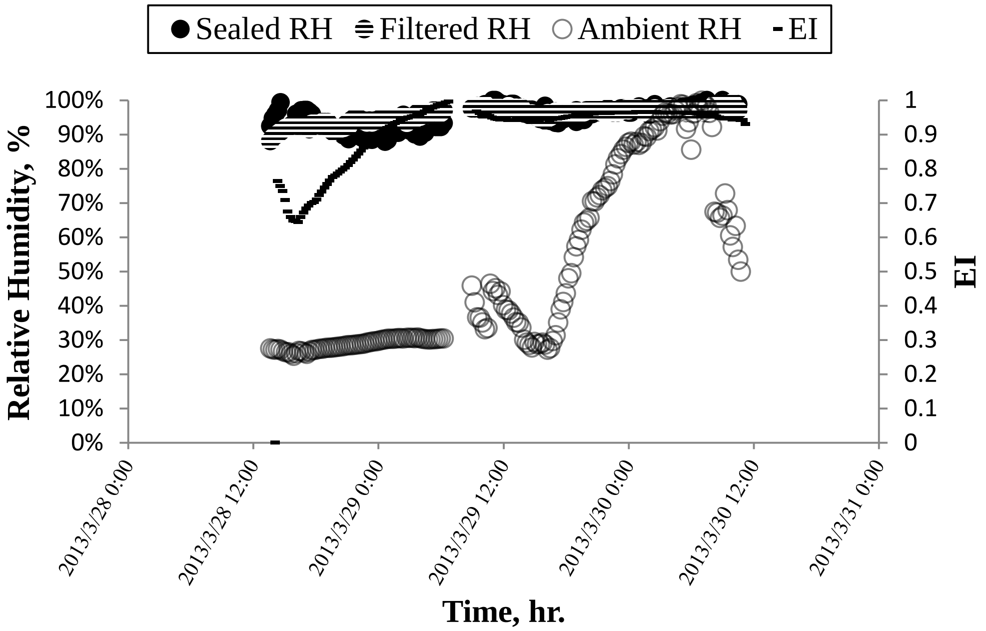

Figure B-3 Relative Humidity data for Section #3

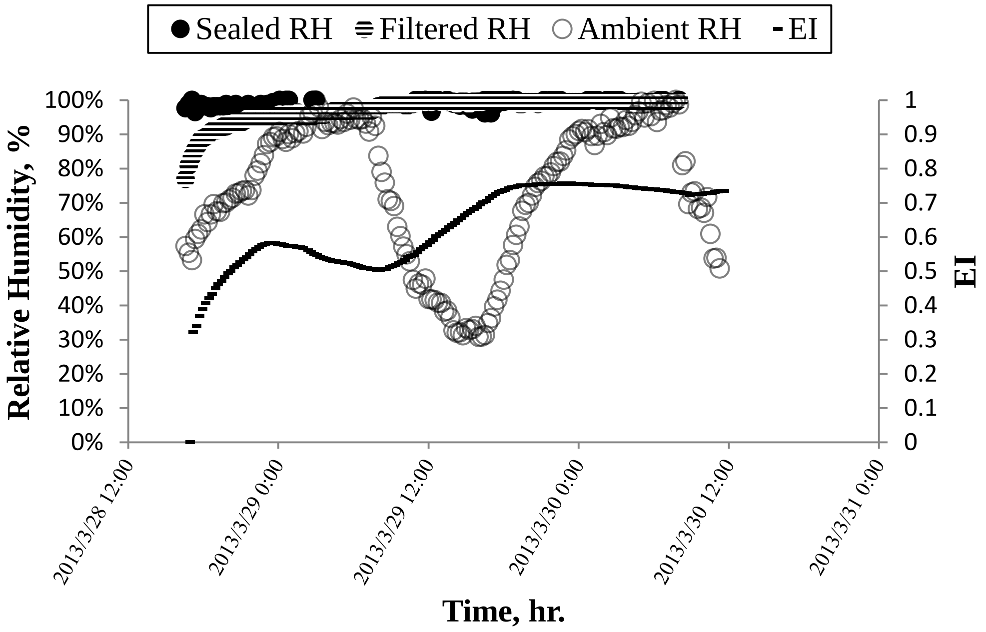

Figure B-4 Relative Humidity data for Section #4

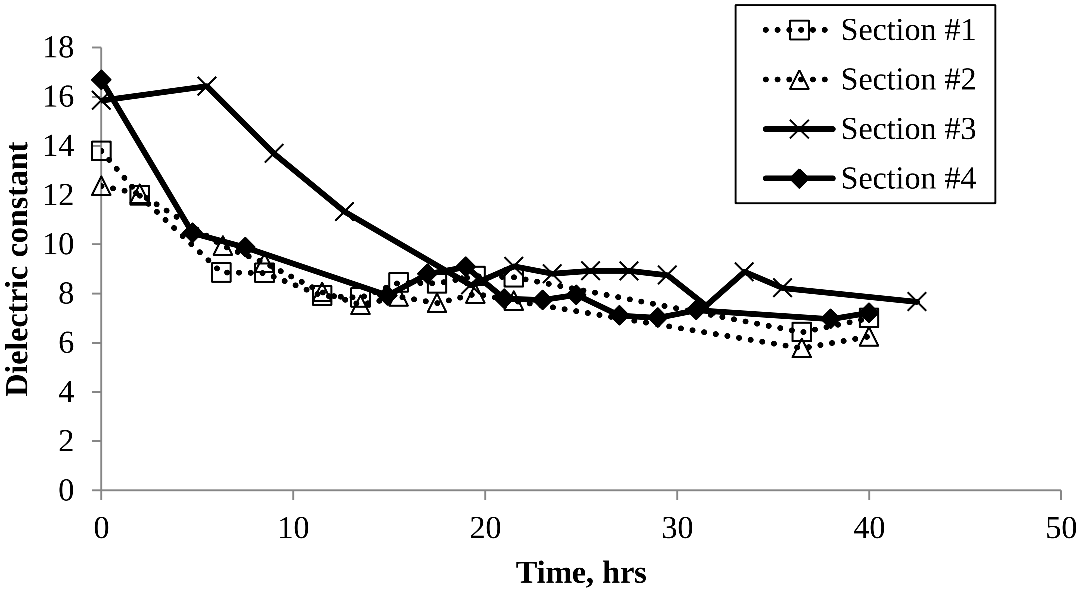

Figure B-5 DC measurements for the field investigation