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16. Abstract

Curing has substantial effects on the long-term performance of Portland cement concrete (PCC) pavement. TxDOT requires two applications of curing compounds, with a maximum 180 sf/gal per each application. However, no compliance testing is conducted for curing and, from a practical standpoint, compliance with specification requirements are rarely verified. The purpose of this research was to identify simple testing procedures that can be implemented to verify the compliance with specification requirements on curing. To this end, various test methods that appear to have potential for compliance testing for curing were evaluated in the field. The test methods evaluated include penetration resistance, initial surface adsorption, surface temperature, reflectance, relative humidity, and dielectric constant. A factorial experiment was set up for field testing, and the test methods were evaluated in the field. Varying rate of curing compound applications as well as application time was included as variables in the factorial experiment. Advantages and limitations of each method were identified and discussed. Based on the findings, it is concluded that the methods evaluated are neither practical nor accurate enough to be included in TxDOT specifications as a compliance testing. Rather, it appears that evaluating curing compound application rates by measuring curing cart speed could present most feasible method for compliance testing.

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Identification of Compliance Testing Method for Curing Effectiveness

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Acknowledgments

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Products

This report contains Product 2. Detailed documentation of the research performed is included in this report.

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1. INTRODUCTION

1.1 RESEARCH BACKGROUND

Hydraulic cement requires adequate moisture and temperature to develop cement hydration for a sufficient period of time. If the moisture content in concrete is not sufficient or the temperature is too low, hydration will not proceed and the concrete may not have desired strength and durability. Proper curing of concrete is crucial to obtain design strength and maximum durability, especially for concrete exposed to extreme environmental conditions at early age. The Texas Department of Transportation (TxDOT) has recently experienced cases of spalling and delamination failure that may be related to high evaporation rate under extreme field conditions, such as high temperature, low humidity, and strong wind.

It is not easy to evaluate whether the current requirements in curing (quality and application rate of curing compounds and timing of compounds application) are met in the field. In most of the projects, the importance of curing has not been recognized and strictly enforced. This problem is partly due to a lack of any compliance testing for the evaluation of curing effectiveness. Therefore, it is necessary to identify a simple test procedure that can evaluate the effectiveness of various curing compounds and eventually the compliance with the specification requirements.

1.2 OBJECTIVE OF THE RESEARCH

There is no acceptable compliance testing method that could be used for the evaluation of curing effectiveness. Because of the unavailability of compliance testing, most of the state departments of transportation (DOTs) utilize method specifications for curing. TxDOT is not an exception. As state DOTs are moving towards performance-related specification, an accurate and reliable compliance testing for curing effectiveness is needed.

The primary objective of this research is to identify appropriate compliance testing for curing effectiveness. There are a number of potential compliance testing devices. In this research, those potential devices were evaluated and limitations were discussed.

1.3 SCOPE OF THE RESEARCH

This research focuses on identifying a suitable evaluation method for measuring the curing effectiveness on the pavement at construction. Curing effectiveness material parameters and relevant devices were investigated in the developed experimental program. Investigated are such parameters as penetration resistance, surface temperature, initial surface adsorption, reflectance, relative humidity, and dielectric constant. Different curing conditions as well as application time and rate of curing compound were covered in the program. Based on measured data, the applicability of each material parameter and relevant devices was discussed.

This research project is a joint research project and The University of Texas at Austin's Center for Transportation Research's (CTR) main task is to develop a field testing program; conduct field measurement; and identify appropriate compliance testing for curing effectiveness.

Different tasks on the development of laboratory test protocol and relevant ranking system were conducted by Texas A&M University's Texas Transportation Institute (TTI) and the results were discussed in a separate report.

2. FIELD COMPLIANCE TESTING

2.1 INTRODUCTION

As described earlier, the current TxDOT specifications on curing in Item 360 are based on vague scientific evidence and there is no compliance testing included in the specifications. The curing in Item 360 is purely a method-type specification and thus the quality of the curing operation is not quantitatively measured. Furthermore, it is not easy to evaluate whether the current requirements in curing are met in the field. Therefore, it is necessary to identify a field compliance testing for curing effectiveness that is related to performance-type specification.

Because the ultimate goal of proper curing is to develop appropriate concrete properties, the adequacy of curing is most readily observed in the properties at the curing-affected zone (CAZ) (Cather, 1992). The curing-affected zone will vary in thickness depending on the properties of the concrete, the severity of the ambient conditions, and the curing time involved. Regardless of the shallowness of the zone, the concrete properties in this zone are most frequently those that determine the durability and serviceability of concrete. Given the shallowness of the curing-affected zone, test methods that evaluate the properties of the concrete at depth, such as measuring the compressive strength of drilled cores, have limited sensitivity to the effectiveness of curing. Table 2.1 shows the concrete characteristics that are likely to be more sensitive to curing effectiveness in the curing-affected zone (ACI 308R-01).

Table 2.1: Concrete characteristics in the curing-affected zone (ACI 308R-01)

Properties near surface affected by curing	
Degree of hydration	Pore size distribution
Oxygen or air permeability	Initial surface absorption
Surface permeability/absorption	Internal moisture content
Tension strength of pull-off testing	Depth of carbonation
Abrasion resistance	

Based on Table 2.1, the applicability of various material properties that monitor the curing effectiveness was identified. A field testing program was developed and potential compliance testing devices were investigated. Included are such parameters as penetration resistance, initial surface adsorption, evaporation heat, reflectance, relative humidity, and dielectric constant. Different curing conditions, which include sealing, no curing and curing compound were simulated in the field test. Additionally, different coating of curing compound that covers application rate and time was also covered. Measured results and the limitation for each material parameter and relevant device are discussed in this chapter.

2.2 PENETRATION RESISTANCE

2.2.1 Introduction

The strength of concrete has a close relationship with the curing effectiveness, especially near the surface exposed to environmental conditions. Good curing condition maintains the moisture content which is used in the hydration process of concrete. The different curing effectiveness may make a difference of strength of concrete near the surface.

A device called Windsor, which uses a powder-activated driver to fire a hardened ally probe into the concrete, can measure the penetration resistance of concrete (Fig. 2.1). The penetrated or exposed length of the probe has a close correlation with the compressive strength of concrete. This approach is currently applied to nondestructive testing methods on concrete strength and durability (Neville, 1995). Fig. 2.2 indicates that the Windsor probe penetrates deeper as the strength of the concrete decreases (ACI 228.1R-03).

The Windsor probe system was applied to measure the penetration resistance, which has a close relationship with the strength of concrete. Different curing conditions were simulated. The correlation between penetration depth and curing effectiveness was measured and its results are discussed in this section.

Figure 2.1: Windsor probe system

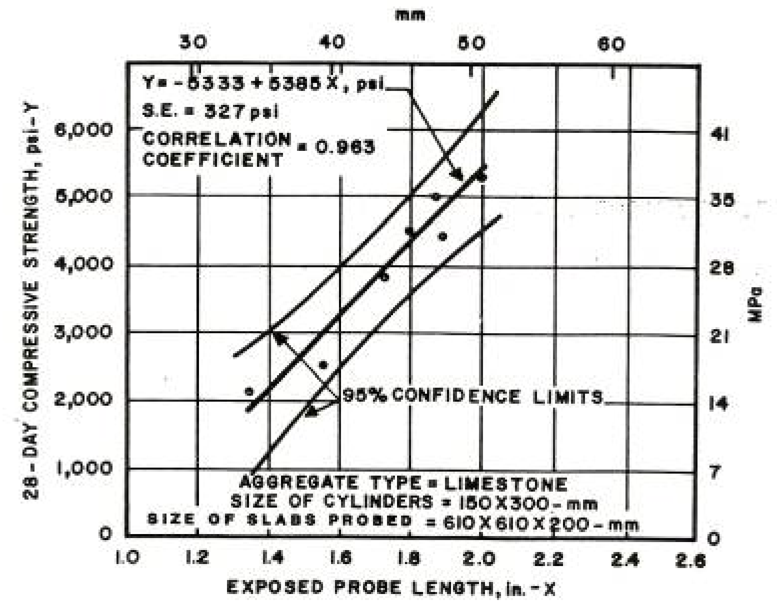


Figure 2.2: Compressive strength as a function of exposed probe length (ACI 228.1R-03)

2.2.2 Field Testing

In order to identify the relationship between curing effectiveness and penetration depth, five different curing conditions were simulated on the surface of pavement at construction. Each testing area had 4ft-width and 4ft-length. As shown in Fig. 2.3, the application rate of the curing compound was controlled by placing a plastic sheet when the paver passed the testing section. Normal white pigmented curing compound from W.R. Meadow was used in the test. Three different rates of curing compound, i.e., one coating, two coating, and three coating of $180ft^2/gal$, were sprayed on each testing area. Additionally, no curing condition and sealing curing condition were also simulated. Table 2.2 summarizes five different curing conditions at the field test.

Three probes were fired on each testing surface of the concrete at the age of 1 day, and Fig. 2.4 shows the probes that penetrated the concrete pavement. The average penetration depth was calculated from three probes

Table 2.2: Five different curing methods at the field test

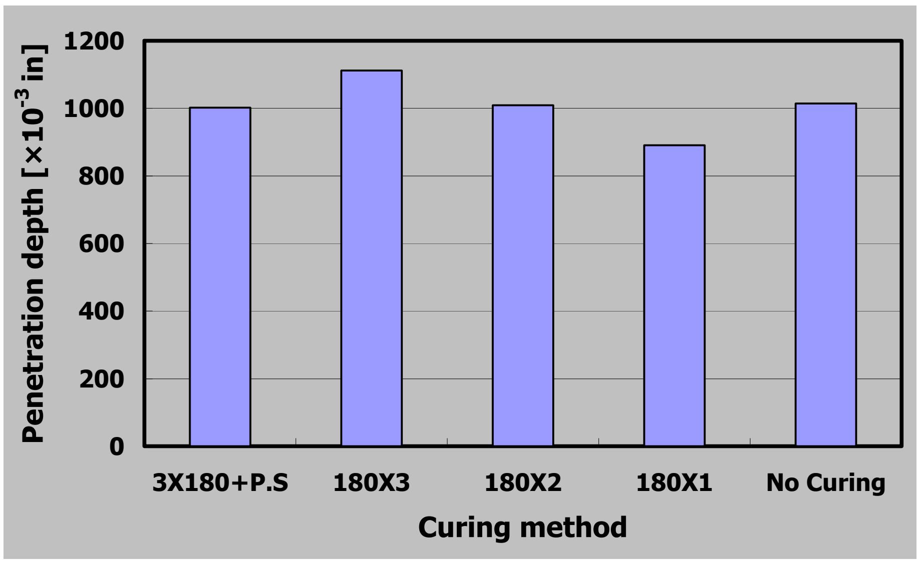
Number	Curing method
Condition 1	Curing compound with $45ft^2/gal$ and plastic sheet
Condition 2	Curing compound with $45ft^2/gal$
Condition 3	Curing compound with $90ft^2/gal$
Condition 4	Curing compound with $180ft^2/gal$
Condition 5	No curing

Figure 2.3: Control of application of curing compound with plastic sheet

Figure 2.4: Field application of the Windsor probe system

2.2.3 Results and discussion

Fig. 2.5 shows the average of penetration depth of three probes according to different curing conditions. As shown in Fig. 2.5, the penetration depth did not show a good correlation with the curing method. The application of the plastic sheet with three coatings of curing compound is considered the most favorable curing condition and thus is expected to have the minimum penetration depth. However, the minimum penetration depth occurred in the concrete with one coating of compound even though the curing condition was relatively poor.



(Note: 3×180+P.S - three coatings of 180ft^2/gal and plastic sheeting; 180×3- three coating of 180ft^2/gal; 180×2 – two coatings of 180ft^2/gal; 180×1- one coating of 180ft^2/gal)

Figure 2.5: Penetration depth vs. curing method

This is because of aggregate in the concrete near the probe. The size of the probe is relatively small and thus the penetration depth is affected by the distance between the probe and aggregate. For example, the depth would be decreased significantly when the probe penetrates and hits the aggregate in concrete. Therefore, aggregate may have more effect on the penetration resistance depth rather than the difference of compressive strength caused by curing method. Because of the small volume of probe under testing, the Windsor probe system is known to have a higher variation compared with the variation in standard compressive strength tests on companion specimens. Furthermore, it was very hard to make a perpendicular penetration of the probe to the surface of the concrete pavement. The deviation from the perpendicularity may cause another error. Therefore, penetration resistance technique and the Windsor probe system may not be a practical method to measure the curing effectiveness in the field. More study is needed to implement this technique in the field.

2.3 SURFACE TEMPERATURE

2.3.1 Introduction

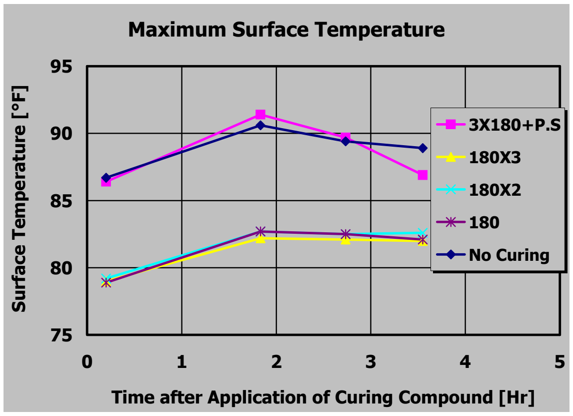
According to ACI nomograph (ACI 308R-01), the evaporation rate of concrete at surface depends on the air temperature, air relative humidity, concrete temperature, and wind velocity. Concrete exposed to environmental conditions also has different evaporation rates at the surface depending on the curing effectiveness. Evaporation accompanies the consumption of heat energy which results in temperature drop in concrete. Therefore, the difference of surface temperature may identify the different evaporation rate and the corresponding curing effectiveness.

2.3.2 Field Testing

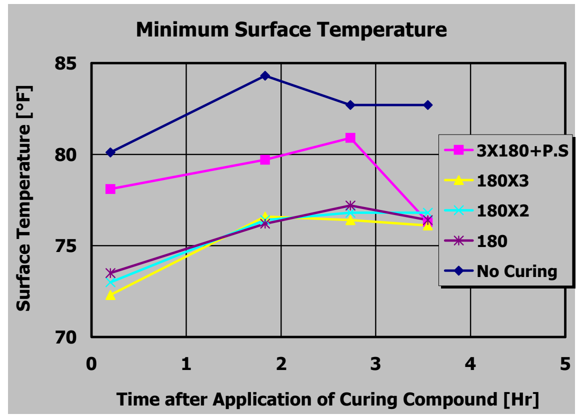
As described in section 2.2.2, five different curing conditions were applied to the testing areas. Three different rates of curing compound, i.e., one coating, two coating, and three coating of 180ft^2/gal, were sprayed on each testing area. Additionally, no curing condition and sealing curing condition were also applied. Infrared camera was adopted in the surface temperature measurement. Fig. 2.6 shows the measurement of surface temperature by infrared camera.

Figure 2.6: Surface temperature measurement by infrared camera

Fig. 2.7 represents the variation of surface temperature by infrared camera. Infrared camera can plot the temperature contour, which shows the maximum and minimum temperature in the shot. Because the concrete exposed directly to environmental conditions (no curing) has the highest evaporation rate, the surface temperature is expected to be lowest. However, the highest temperature was recorded in no curing condition at 2 hours after the placement. This is due to the color difference between fresh concrete with curing compound and concrete without curing compound. The color of fresh concrete without curing compound is close to black. On the other hand, the curing compound has a white pigment. Therefore, more solar radiation energy was absorbed in the concrete without curing compound and this resulted in the highest temperature among specimens with different curing conditions.



(a) Maximum surface temperature



(b) Minimum surface temperature

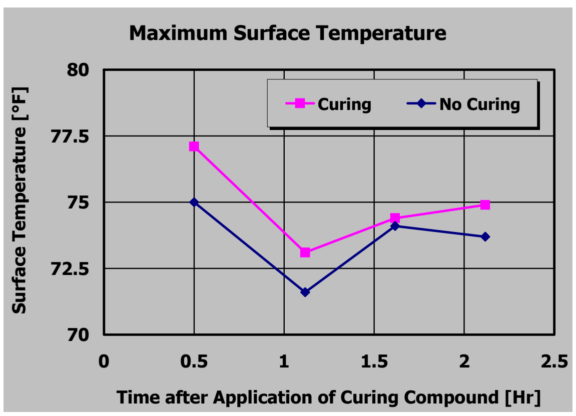
(Note: 3×180+P.S - three coatings of $180ft^2$/gal and plastic sheeting; 180×3- three coating of $180ft^2$/gal; 180×2 – two coatings of $180ft^2$/gal; 180×1- one coating of $180ft^2$/gal)

Figure 2.7: Surface temperature variations with different curing methods

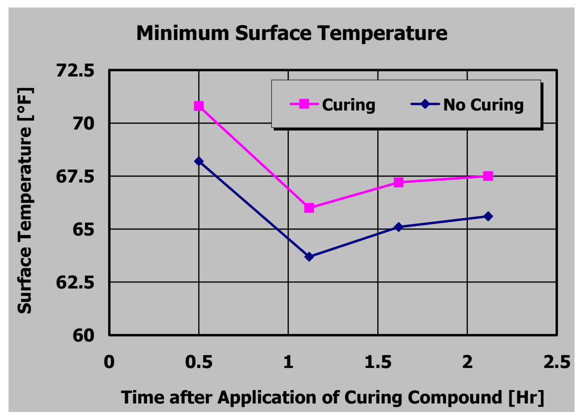
To exclude the effect of solar radiation on the surface temperature of concrete pavement, sun screen was placed on the surface of concrete pavement and the temperature with the screen was measured (Fig. 2.8). Two different curing conditions were applied to testing areas. In the first condition, curing compound was sprayed two times at the rate of $180ft^2$/gal. No curing compound was applied and the top surface of the concrete was directly exposed to air in the second condition. Infrared camera was adopted in the surface temperature measurement.

Fig. 2.9 shows the measured temperature variations. Contrary to the surface temperature without sun screen, the surface temperature of the concrete covered with curing compound had the higher temperature than that of the concrete without curing compound. More evaporation energy and corresponding temperature drop was measured under the condition in which the direct solar radiation was excluded.

Figure 2.8: Surface temperature measurement within sun screen



(a) Maximum surface temperature



(b) Minimum surface temperature

Figure 2.9: Surface temperature variations within sun screen

2.3.3 Discussion

Incident radiation might tend to obscure the observed temperature effect, particularly with white-pigmented curing compounds. The high level of reflectance of these materials would tend to have the opposite effect on surface temperature relative to the evaporative effects. The same effect would not appear to apply to clear curing compounds. Given the relatively small temperature and transient difference that was observable under relatively high levels of evaporation, this technique does not appear to have promise for general field use, given the complicating effects of sunlight and variable evaporation conditions that might exist in the field.

2.4 INITIAL SURFACE ABSORPTION

2.4.1 Introduction

The rate of water absorption by capillary suction is a good measure of the quality of a concrete and its potential durability (Neville, 1995). Low values of absorption indicate that aggressive ions will have difficulty in penetrating concrete. Experimental research indicates that the water absorption values are reduced with decreases in water-cement ratio. Furthermore, the absorbed amount of water at the surface decreases as the curing quality improves (Olliver et al., 1995). Therefore, initial surface absorption may be a good indicator for curing effectiveness at the surface of concrete.

2.4.2 Field testing and discussion

Based on the existing research results, a field test was conducted to identify the curing effectiveness in terms of initial water absorption at the surface (Fig. 2.10). A funnel was installed on the surface when the concrete was poured. To seal the interface between the funnel and concrete surface, epoxy was applied after hardening of the concrete. Water was poured into the funnel. Fig. 2.10 (a) shows the successful installation of the funnel for the measurement of initial surface absorption. Most of the installed funnels, however, had water leakage problems, as shown in Fig. 2.10 (b). It is considered that the surface absorption measurement is not easy to implement and thus it is not a practical field compliance method for curing effectiveness.

(a) Funnel without water leakage (b) Funnel with water leakage

Figure 2.10: Surface absorption measurement in field

2.5 REFLECTANCE

2.5.1 Background

Reflectance is a measurement commonly used in the paint industry to measure degree of whiteness (ASTM E 1347-06). As shown in Fig. 2.11, reflectance is defined as the ratio of incident flux on a sample surface to reflected flux from the surface. More light would be reflected as the whiteness of the sample surface increases (Fig. 2.12). This measurement technique can be applied to measure the application rate of curing compound.

The basic idea is that the color of the concrete surface would be closer to the white as more curing compound is sprayed (Fig. 2.13). The reflectance would be proportional to the application rate of the curing compound. Therefore, the reflectance measurement can differentiate the application rate as well as the uniformity of the curing compound in concrete pavement at construction.

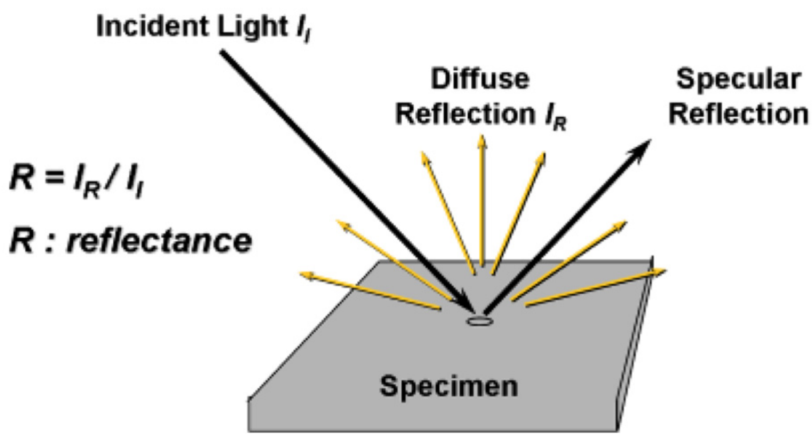


Figure 2.11: Definition of reflectance

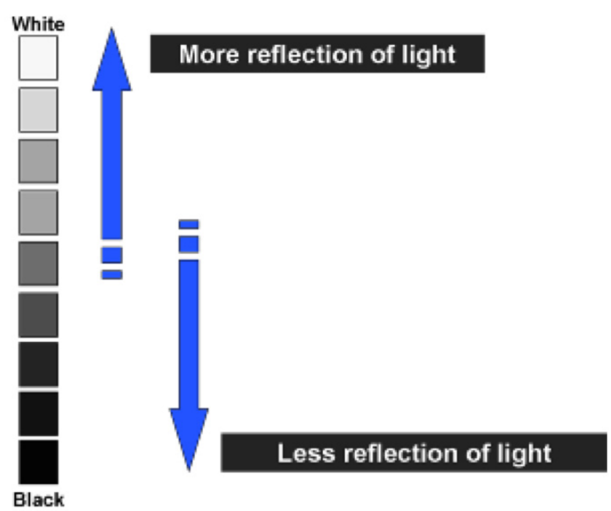


Figure 2.12: Variation of reflectance depending on the whiteness

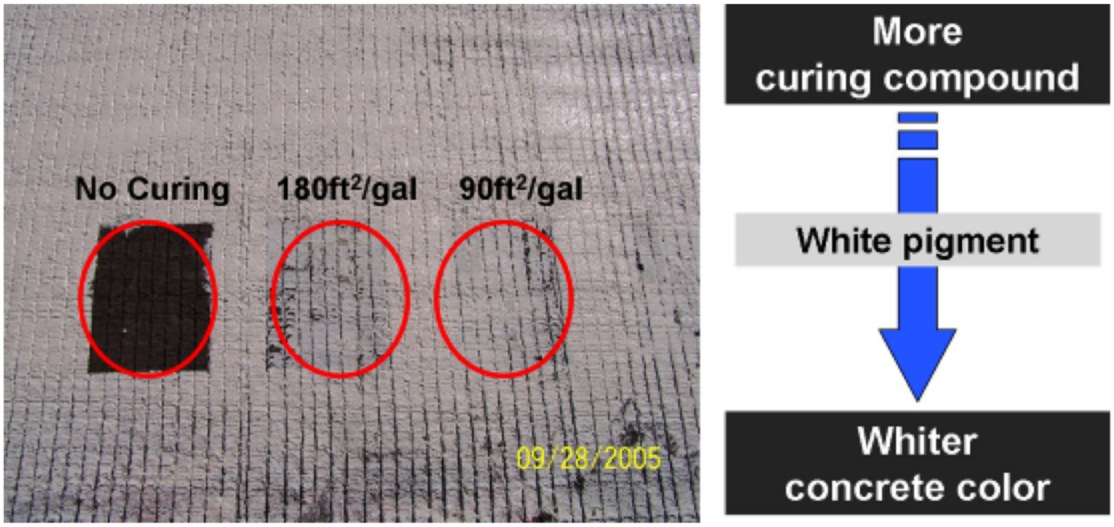


Figure 2.13: Color difference by different application rates of curing compound

To investigate the applicability of this approach, a reflectometer was used to measure the whiteness of the concrete specimen. A reflectometer adopts the photocell which can measure the intensity of reflected light (Fig. 2.14). The test surface is illuminated from a 45° angle. The intensity of scattered light at the perpendicular (i.e., 0°) is measured. Data is recorded on a grey scale where black is 0% and white is 100%. Only shading is measured, irrespective of color, and is referred to as whiteness. Laboratory and field tests were conducted and results are discussed in this section.

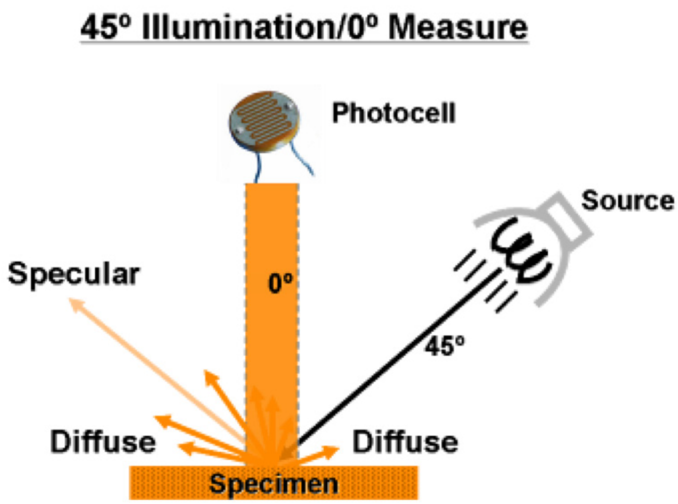


Figure 2.14: Reflectometer

2.5.2 Laboratory test

To develop the standard relationship between the reflectance and the application rate of the curing compound in the concrete specimen, laboratory testing was conducted. Fig. 2.15

shows the procedure in laboratory testing. Disk specimens with a 14-inch diameter were made and their weights were measured before application of the curing compound. Different amounts of curing compound were sprayed to the specimens. The weight of the specimen was measured again after spraying the curing compound to find out the application rate of the curing compound.

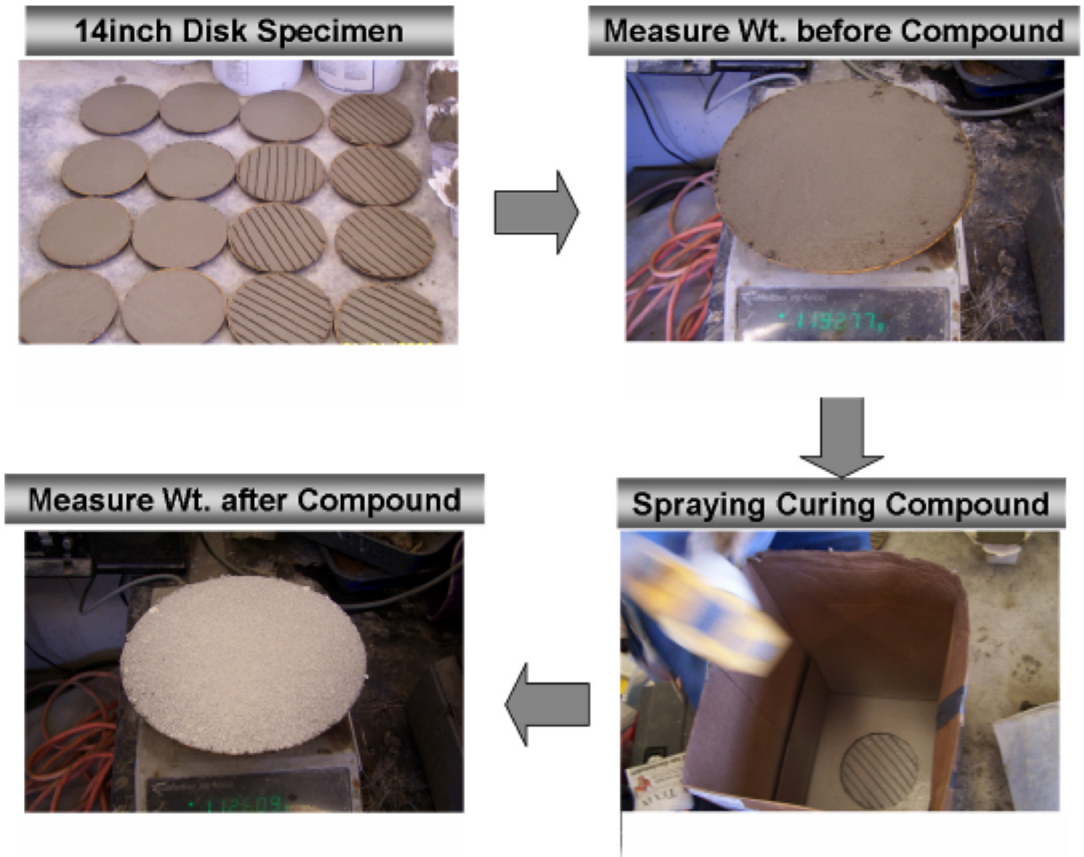


Figure 2.15: Laboratory test procedure

The reflectance of each specimen that had the different application rate of curing compound was measured by reflectometer (Fig. 2.16). As shown in Fig. 2.17, the measured reflectance shows a good correlation with the application rate of the curing compound. The reflectance decreased with decrease of the application rate of the curing compound.

The application rate of the curing compound in TxDOT specifications is two coatings of 180ft^2/gal. The corresponding reflectance to the specified rate (90ft^2/gal) was 77 percent, as shown in Fig. 2.17. This value can be employed as the reference to evaluate whether the current requirements in the application rate of the curing compound are met in the field.

Figure 2.16: Reflectance measurement of disk specimen

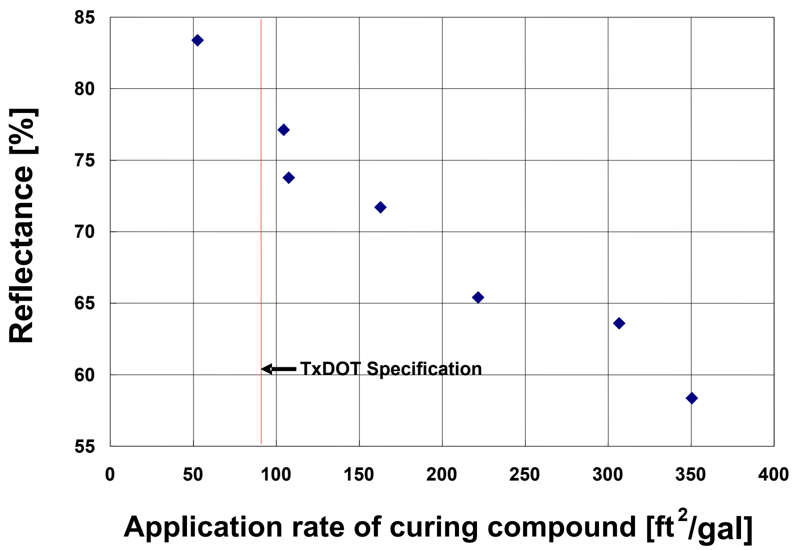


Figure 2.17: Application rate of curing compound vs. reflectance

2.5.3 Field testing

In order to investigate the applicability of reflectance measurement in the field, field testing was conducted. Fig. 2.18 shows the calibration procedure of the reflectometer before reflectance measurement. Reflectometer was calibrated with the ideal black and white bar, which had 0 percent reflectance and 100 percent reflectance, respectively.

After calibration, measuring points which seemed to have the different application rate were selected by visual estimation. In order to prevent the effect of sunlight outside, the reflectometer was placed inside the cardboard and the reflectance were measured in the shadowed area. Fig. 2.19 shows a series of reflectance measurements on which the different rates of the curing compound were applied. The concrete was tested at one day later from the placement. Measured reflectance showed a good agreement with visual estimation. As the thicker curing compound was sprayed, higher reflectance was observed.

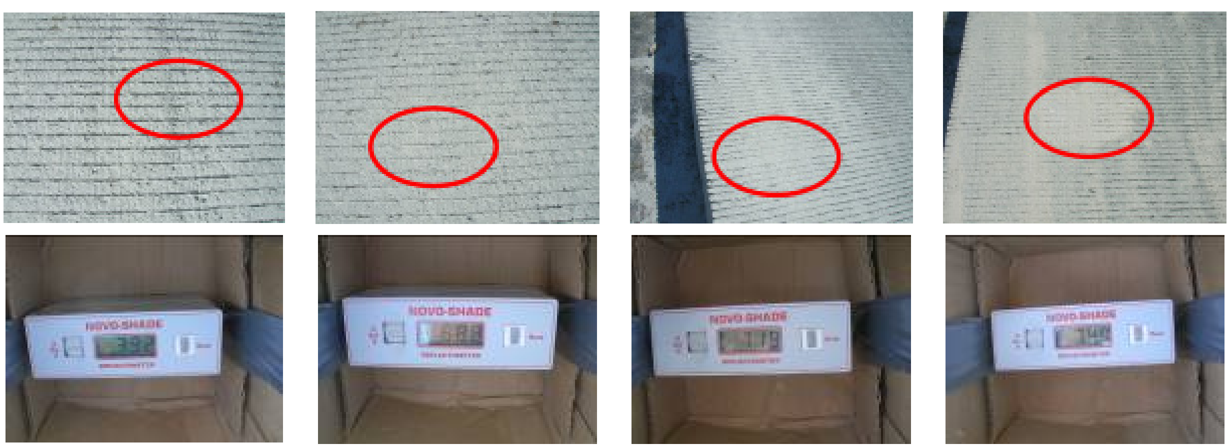
(a) Ideal white bar

(b) Ideal black bar

(c) Calibration of 100 percent reflectance

(d) Calibration of 0 percent reflectance

Figure 2.18: Calibration of reflectometer



(a) 39.2 percent (b) 68.8 percent (c) 71.9 percent (d) 74.4 percent

Figure 2.19: Differences of measured reflectance based on visual estimation

To quantitatively identify the correlation between reflectance and the application rate of the curing compound, the application rate of the curing compound was controlled in the field and corresponding reflectance was measured at 5 hours later from the placement of concrete. Fig. 2.20 represents the variations of reflectance according to the rate of curing compound. Three different rates of curing compound—i.e., no curing, 162 ft^2/gal, and 81 ft^2/gal—were applied and the measured values of reflectance were 15 percent, 49.2 percent, and 77.4 percent, respectively. As in the laboratory test, the reflectance increased with the increased amount of curing compound.

No curing | 162 ft^2/gal | 81 ft^2/gal

(a) Reflectance: 15 percent (b) Reflectance: 49.2 percent (c) Reflectance: 77.4 percent

Figure 2.20: Reflectance vs. rates of curing compound in the field

2.5.4 Spatial distribution of reflectance in concrete pavement

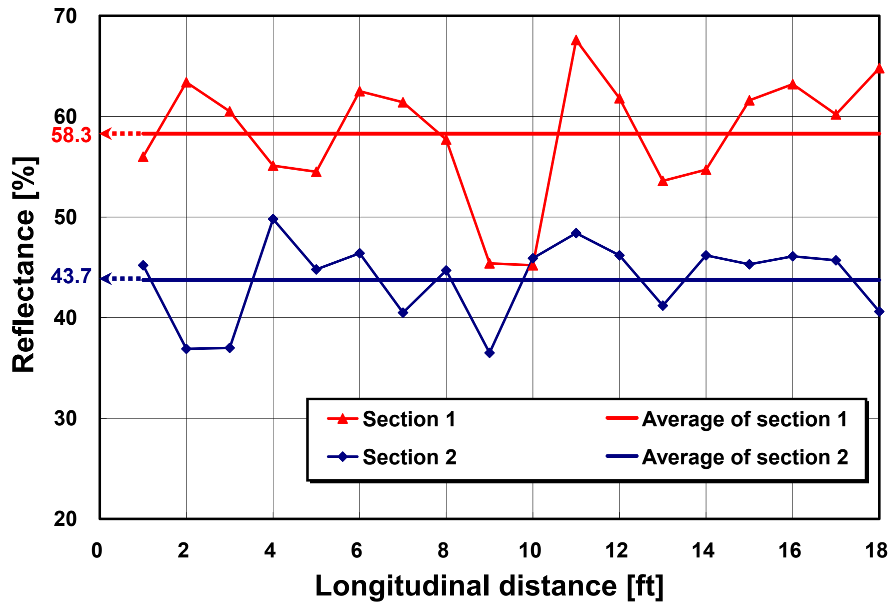
The application rate of the curing compound depends on the nozzle condition, nozzle angle, nozzle spacing, cart speed, and pressure in the spraying machine. If the condition of each nozzle is different, the curing compound would be sprayed differently and may cause different distributions of curing compound in the transverse direction (Fig. 2.21). To evaluate the uniformity and spatial distribution of the curing compound in situ, reflectance was measured in the transverse direction as well as longitudinal direction at 1-ft spacing. The age of concrete in which the reflectance was measured was one day.

Based on a visual survey, four sections that seemed to have different application rates of curing compound were selected and the reflectance was measured in the longitudinal direction (Fig. 2.22). In order to investigate the uniformity of the curing compound caused by the different nozzle condition, reflectance was also measured in the transverse direction.

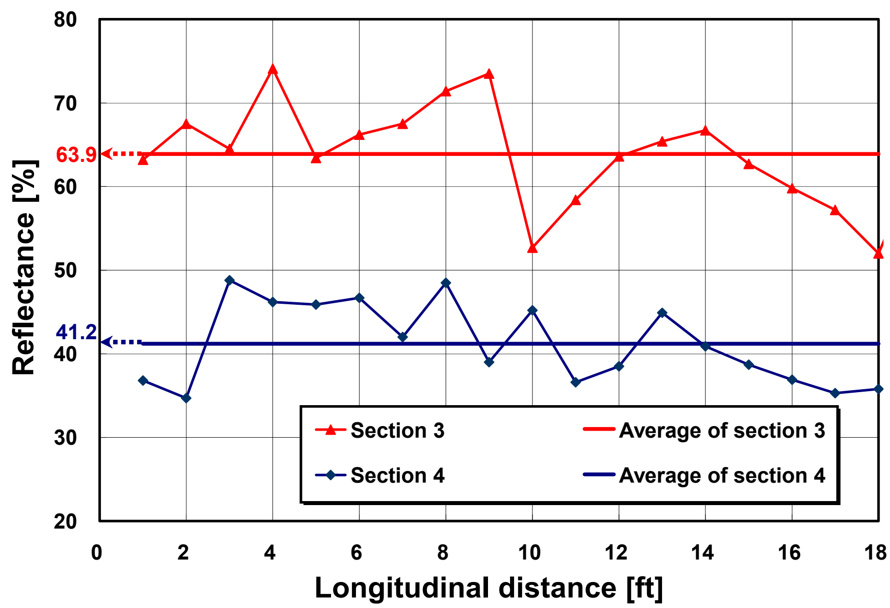
Figure 2.21: Non-uniform distribution of curing compound in the field

Figure 2.22: Reflectance measurements in longitudinal direction

Fig. 2.23 represents the longitudinal distribution of reflectance in the field. The averages of reflectance in sections one and three that seemed to have sufficient application rates were 58.3 percent and 63.9 percent, respectively. On the other hand, the averages of reflectance in sections two and four were relatively small (43.7 percent and 41.2 percent), and these were due to the poor application rates. It indicates that the reflectance measurements have a good agreement with the visual survey. Fig. 2.24 represents the reflectance contour, which represents the spatial distribution of reflectance in the transverse direction as well as longitudinal direction. As shown in Fig. 2.24 (a), less variation of reflectance was measured in good application of the curing compound. In case of poor application, not only was the average of reflectance smaller but also the variation was more (Fig. 2.24(b)). Fig. 2.24 indicates that the reflectance measurement could represent the spatial distribution of the curing compound and its application rate. Therefore, the application of reflectance might have a potential for field compliance testing that can identify the quality of curing.

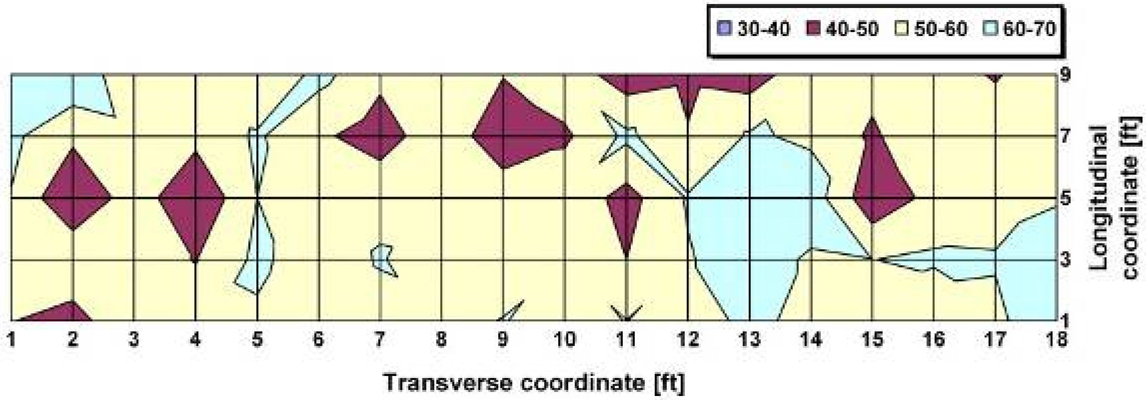


(a) Distribution of reflectance in sections one and two with sufficient application of compound

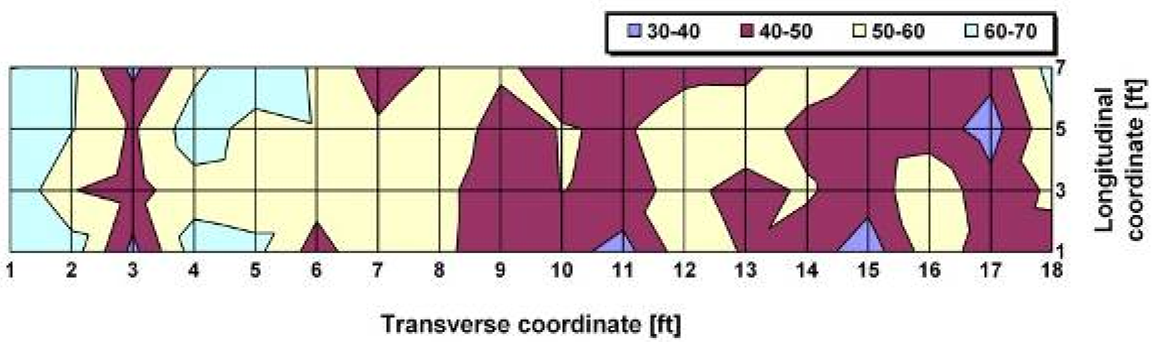


(b) Distribution of reflectance in sections three and four with poor application of compound

Figure 2.23: Longitudinal distribution of reflectance in field



(a) Reflectance contour with good application of curing compound



(b) Reflectance contour with poor application of curing compound

Figure 2.24: Reflectance contour on pavement surface

2.5.5 Limitation of reflectance measurement

Reflectance is defined as the ratio of incident flux on a sample surface to reflected flux from the surface (Fig. 2.11). Because of the tining of concrete pavement, concrete pavement has a rough surface and this roughness causes a crevice between the reflectometer and the pavement surface. If the flux from sunlight could penetrate through the crevice, the reflectance would increase significantly regardless of the color of sample surface, i.e., the application rate of the curing compound. The values of reflectance can be more than 100 percent. Therefore, an additional instrument that prevents the flux from outside should be added to get the accurate and consistent reflectance.

The application of the reflectometer covers a very small area and thus it may be a very labor intensive job if the entire area of pavement is to be measured. Continuous measurement with the memory can overcome this limitation. In order to make this approach feasible in the field, an accessory that makes the reflectometer mobile has to be added. The memory that stores the coordinates of measurement and reflectance values is necessary as well.

2.6 RELATIVE HUMIDITY

2.6.1 Background

As described earlier, the goal of proper curing is to maintain the appropriate temperature level and moisture content in early age concrete. According to the ACI nomograph, surface evaporation of concrete depends on air temperature, concrete temperature, air relative humidity, and wind velocity. As concrete dries, free moisture disappears from the surface due to evaporation. Higher rates of evaporation induce larger moisture variations within the concrete immediately below the surface. If evaporation is minimized by a given curing method, the variation of relative humidity below the surface will be relatively small with time. Therefore, internal relative humidity can be a most promising indicator on the quality of curing operation and curing effectiveness. It can be used as the basic material properties in the field compliance test method. The purpose of this section is to investigate the applicability of relative humidity to the field compliance test method for curing effectiveness.

Laboratory tests and field tests were conducted. Test variables were application rate and time of curing compound. A hygrochron, which has been used extensively in the test during TxDOT Project 0-1700, was adopted as the relative humidity sensor. The variation of relative humidity was measured with time. Measured results and limitation are discussed in this section.

2.6.2 Laboratory testing

In order to investigate the effect of the application time of the curing compound on the internal relative humidity of early age concrete, a laboratory test was conducted. A hygrochron was embedded at the depth of 1/4 inch of the cylinder specimen to measure the internal relative humidity. Curing compound with the rate of 270ft^2/gal was sprayed at different times, i.e., 30 min, 2 hours, and 4 hours after concrete mixing. The cylinder specimens were cured in the environmental chamber, where the temperature and relative humidity were maintained at 73° and 26 percent, respectively (Fig. 2.25).

Fig. 2.26 shows the measured internal relative humidity with time. The most significant drop of relative humidity occurs in the specimen that is exposed to air without any curing compound. On the other hand, the decrease of relative humidity was negligible in a sealed specimen. The entire group of specimens with the curing compound experienced the decreases of the relative humidity with time and the smallest drop occurred in the specimen with an application time of 30 minutes. It indicates that faster application of the curing compound provides more favorable conditions for the control of moisture content in early age concrete.

Figure 2.25: Cylinder specimens with different application time of curing compound

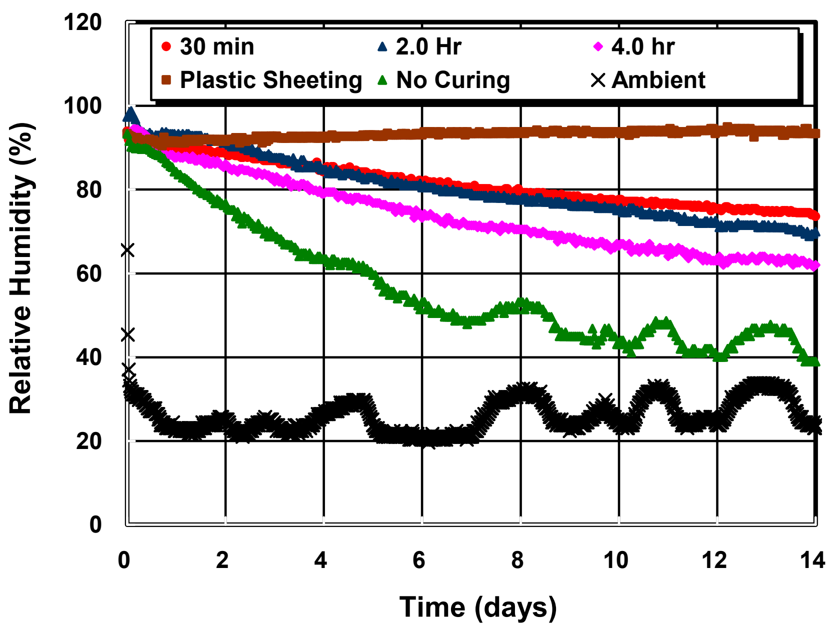


Figure 2.26: Effect of application time of curing compound on relative humidity

Another laboratory test was conducted to investigate the effect of the application rate of the curing compound on the internal relative humidity of concrete. Beam specimens were made and hygrochrons were installed at depths of 0.25 inch and 0.5 inch. Two different types of curing compound, i.e., normal and high reflective compound, were spayed at the rate of 180ft^2/gal, 90ft^2/gal, and 45ft^2/gal. The specimens were cured in the environmental chamber (Fig. 2.27). Figs. 2.28 and 29 show the variation of relative humidity with time when different rates of normal and high reflective curing compound were applied, respectively. Only one specimen which was sprayed with normal curing compound with the rate of 180ft^2/gal experienced a small amount of humidity drop at 0.25-inch depth. In other specimens, the relative humidity was maintained constant or slightly increased rather than decreased. It indicates that the application rate of the curing compound does not make a significant influence on the control of moisture content at a depth of more than 0.5 inch.

Figure 2.27: Beam specimen with different application times and rates of curing compound

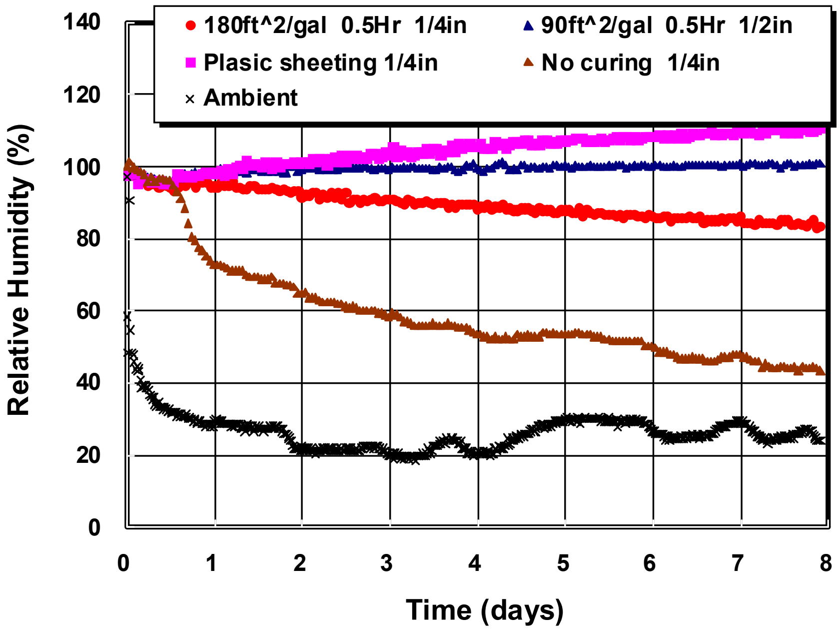


Figure 2.28: Effect of application rate of normal curing compound on relative humidity

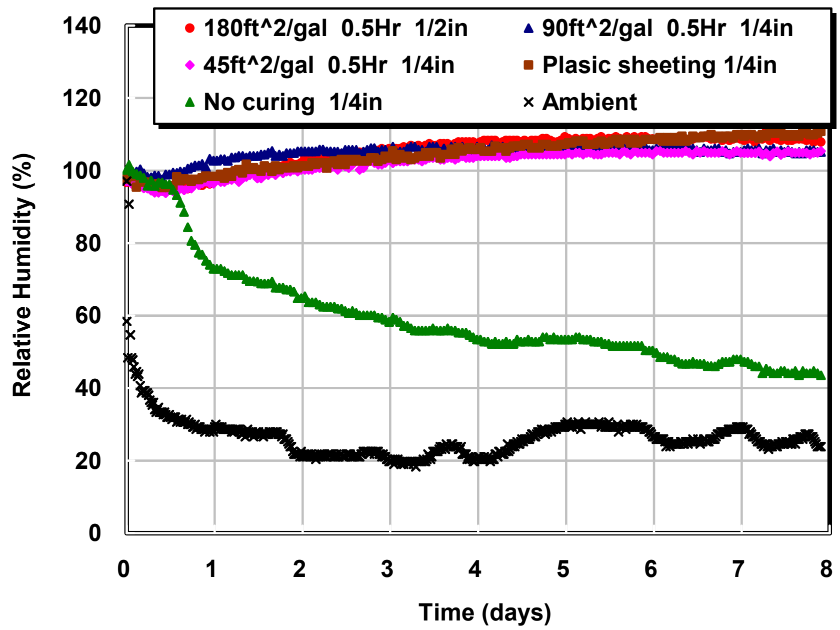


Figure 2.29: Effect of application rate of high reflective curing compound on relative humidity

2.6.3 Field testing

2.6.3.1 Validation of hygrochron with dew point type humidity sensor

To validate the accuracy of the hygrochron, a dew point type humidity sensor—the advanced concrete moisture monitoring system (ACMM)—was installed (Ye et al., 2005) and measured values from both sensors were compared. Both the ACMM and hygrochron were installed at a 1- inch depth in the same testing site (Fig. 2.30), and Fig. 2.31 shows the measured values from the two sensors. The measured relative humidity from the hygrochron is higher than that from the ACMM. However, the variations of both sensors were similar to each other.

One of the reasons for this difference is that the ACMM doesn't allow precise installation because it is relatively big. A slight difference of temperature can make a significant change of RH. Additionally, the chilled mirror has to be kept clean to detect dew point temperature. The ACMM was installed into the fresh concrete and the surface might be contaminated.

Figure 2.30: Comparison of hygrochron with dew point type humidity sensor (ACMM)

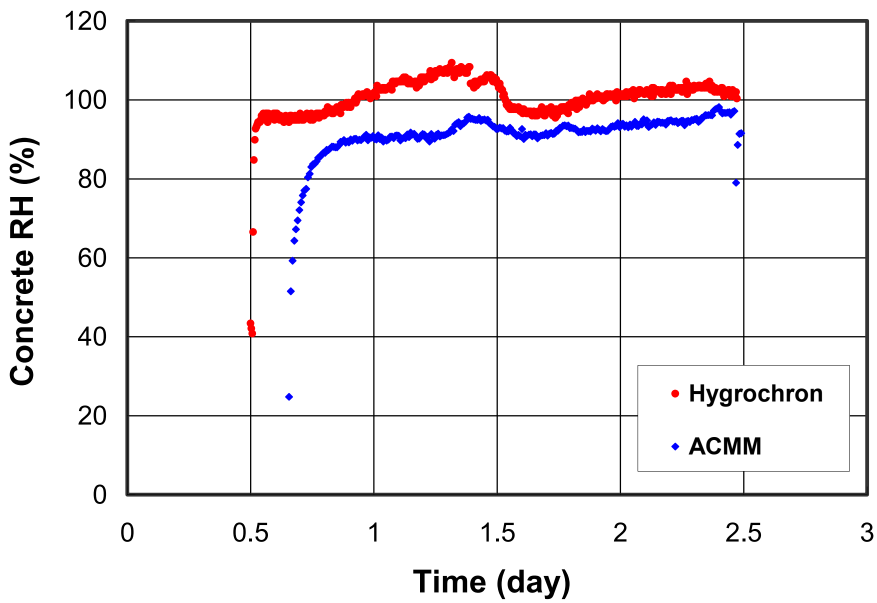


Figure 2.31: Relative humidity from hygrochron and dew point type humidity sensor (ACMM)

2.6.3.2 Relative humidity at different depths in the field

Surface evaporation results in non-uniform distribution of relative humidity along the depth of concrete pavement and the effect of the curing operation may be very sensitive to a confined area, called CAZ (curing affected zone). To experimentally identify the depth that shows a significant variation of relative humidity, hygrochrons were embedded at different depths, i.e., 0.5, 1.0, 6.0 and 11.0 inches from the surface [Fig. 2.32(a)]. An additional sensor was placed at the surface [Fig. 2.32(b)]. Fig. 2.33 illustrates that the hygrochrons installed near the surface portion of the pavement experienced more variation of relative humidity. The most significant variation was measured at the surface. However, there are little changes of relative humidity at depths of 6 inches and 11 inches. It indicates that relative humidity which is affected by surface evaporation varies significantly in the limited zone near the surface of concrete pavement. Therefore, the hygrochron was installed at a depth less than 1.0 inch in the subsequent test.

(a) Hygrochron at middle and bottom depth (b) Hygrochron near surface area

Figure 2.32: Installation of hygrochrons along depth of concrete pavement

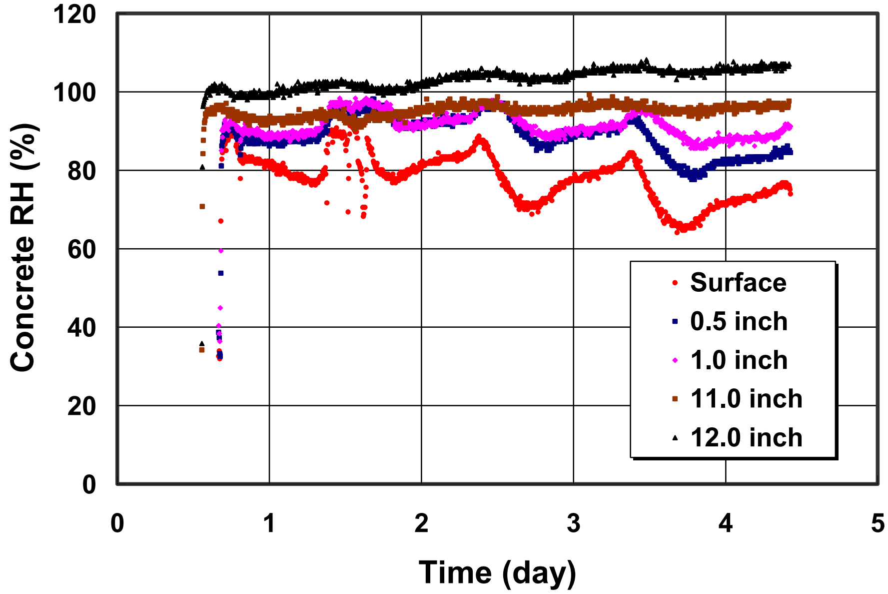
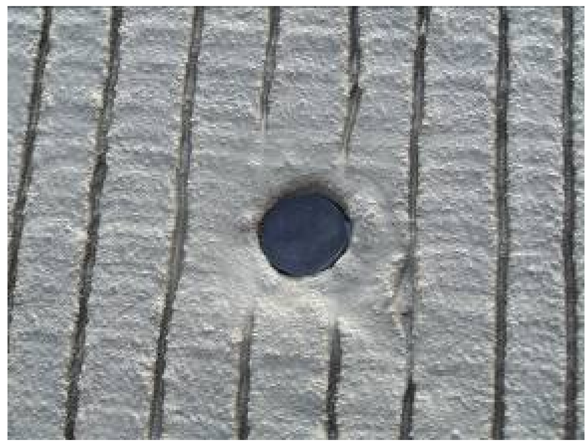


Figure 2.33: Variation of relative humidity along depth of concrete pavement

2.6.3.3 Effect of different curing conditions on relative humidity

In order to identify the influence of different curing conditions on the internal relative humidity of concrete, three different curing conditions, which included sealing, no curing, and curing compound were made in the field test. Curing compound was sprayed two times according to TxDOT specification. Fig. 2.34 shows the simulated different curing conditions and the installed hygrochron in the field. The measured data shows that the internal relative humidity diminishes significantly in no curing condition. Theoretically, the sealing curing condition with the plastic sheet is considered to be most favorable curing condition and thus it is expected that higher relative humidity would occur. However, the relative humidity with the application of curing compound was higher than that with the plastic sheet. Furthermore, the measured relative humidity was more than 100 percent, especially in the test area with the curing compound. The reason for the above phenomena is not clear; and it is considered that more study is required to obtain reliable results on the internal relative humidity.

(a) Different curing conditions



(b) Installation of hygrochron

Figure 2.34: Different curing conditions and field installation of hygrochron

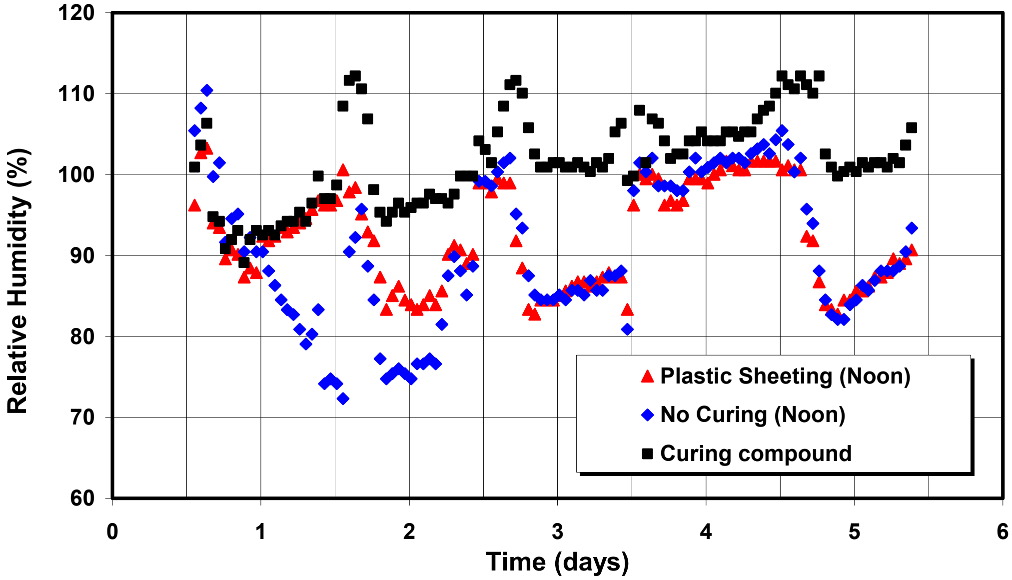


Figure 2.35: Effect of different curing conditions on relative humidity

2.6.3.4 Effect of application time of curing compound on relative humidity

Concrete specimens with 12-inch diameter and 12-inch length were made and cured in the field (Fig. 2.36). Curing compound was sprayed at different times and hygrochrons were installed at a 0.25-inch depth. Figs. 2.37 and 2.38 represent the internal relative humidity depending on the application time of normal and high reflective curing compound, respectively. Normal curing compound was sprayed at two different times. For example, “0.5Hr 1Hr” means that compound was sprayed at 0.5 hour and 1.0 hour later from the mixing of concrete. Fig. 2.37 indicates that the variation of relative humidity had the same tendency regardless of application time. It indicates that the application time of the curing compound does not make a significant influence on the internal relative humidity. The same results were observed in the high reflective curing compound in Fig. 2.38. One possible reason for this result is due to the inaccuracy or instability of the hygrochron.

Figure 2.36: Concrete specimens with different application times of curing compound

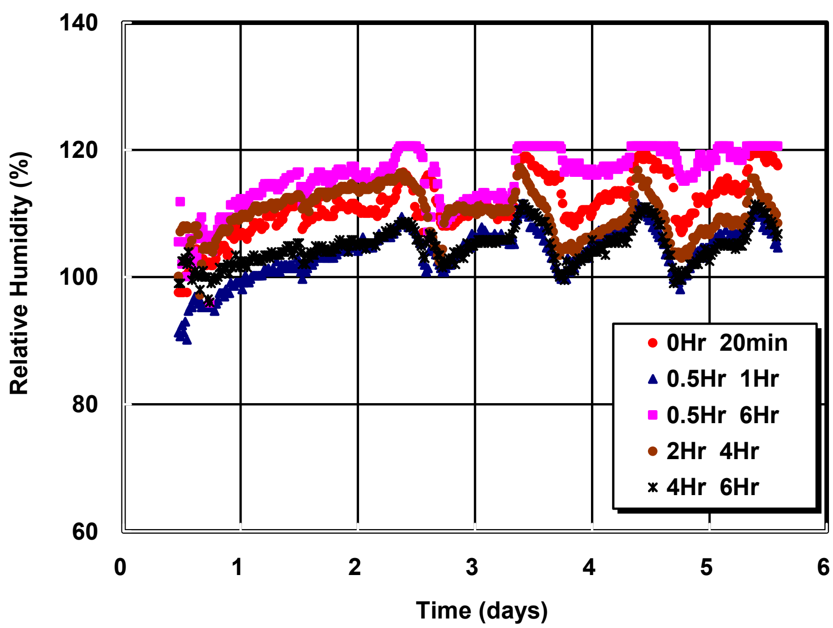


Figure 2.37: Effect of application time of normal curing compound on relative humidity

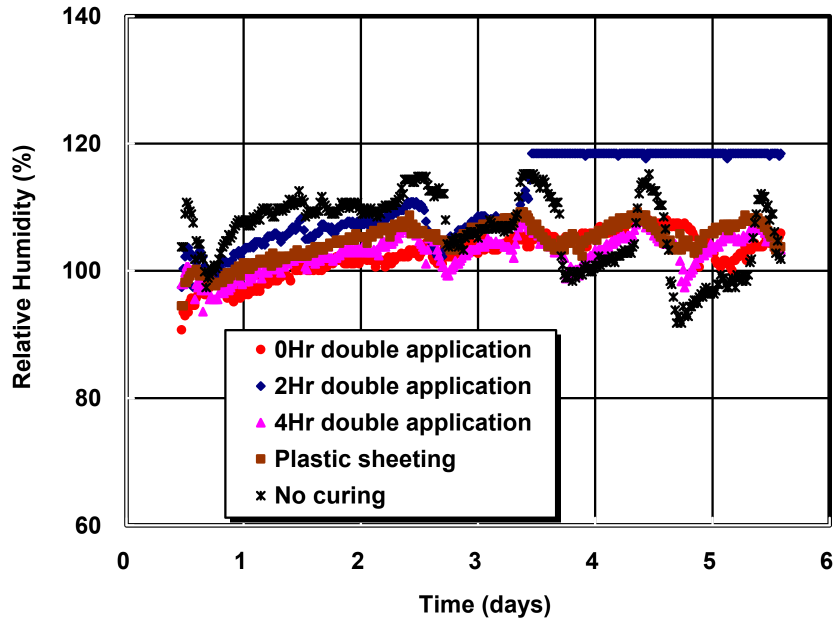


Figure 2.38: Effect of application time of high reflective curing compound on relative humidity

2.6.4 Discussion on relative humidity measurement

Chilled mirror hygrometers measure the temperature of the surrounding air as well as the temperature at which dew forms on a mirror surface (Ye et al., 2005). If the mirror is kept clean, high levels of accuracy can be achieved. While this type of sensor works well for meteorologists, a chilled mirror sensor is not considered practical for the RH measurement in concrete because they are relatively expensive and their relatively large size doesn't allow measurement of RH at precise locations. Additionally, the surface of the mirror is easily contaminated when it is exposed to the fresh concrete. The ACMM in the field test was inconsistent with data from the hygrochron. The reason for this inconsistency may be because of the size of the ACMM and contamination of the mirror surface.

Capacitive sensors measure changes in the capacitance of a thin hygroscopic polymer film as it absorbs moisture (Grasley et al., 2006). RH values are estimated from the reference curve that is calibrated in a precision humidity chamber with a chilled mirror hygrometer. Its accuracy is generally affordable. However, they have reduced accuracy at RH values exceeding 90 percent. The data in the field test showed that RH from hygrochron was more than 100 percent because RH values in this sensor are not directly measured but estimated from the curve which describes RH as a function of capacitance changes. Another issue on capacitive sensors is that capacitive sensors cannot be directly exposed to fresh concrete. To eliminate these issues, plastic pipe with Gore-Tex was used to protect the sensor in this research. Pore size or configuration of this fabric would make an influence on RH values that might not be consistent. A different RH sensor (SHT75) was utilized in the laboratory test and its results are discussed in the next section.

The technology on the internal RH of early age concrete is still under progress and various types of humidity sensors have been tried (Grasley, 2005). However, there are still a lot of improvements to be accomplished to obtain reliable RH in the fresh concrete. Therefore, it is considered that measurement of RH may not be a practical field compliance testing method for curing effectiveness.

2.7 DIELECTRIC CONSTANT

2.7.1 Introduction

The dielectric constant is the ratio of the permittivity of a substance to the permittivity of free space. It is an expression of the extent to which a material concentrates electric flux and is the electrical equivalent of relative magnetic permeability. Theoretically, the dielectric constant has a correlation with the moisture content in concrete (Laurens et al., 2003). The more moisture concrete has, the dielectric constant will be higher (Fig. 2.25). This approach can be applied to identify the curing effectiveness. The moisture content in the surface region of concrete pavement (curing affected zone) has a close relationship with the curing effectiveness and thus the dielectric constant can represent the curing effectiveness.

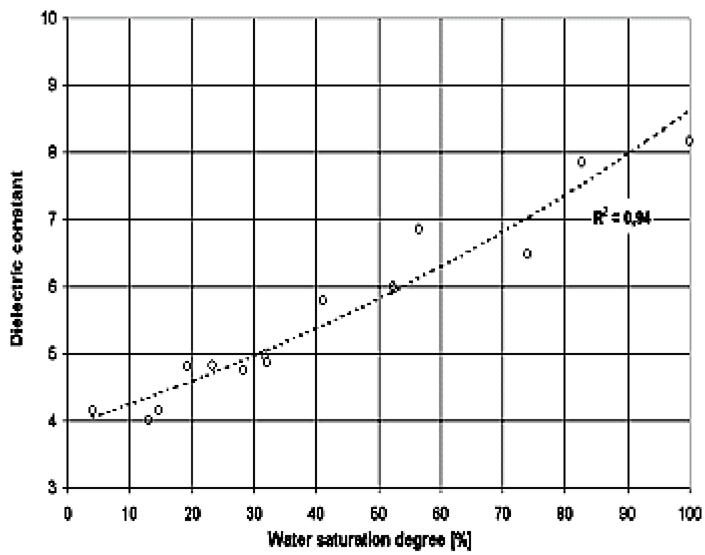


Figure 2.39: Dielectric constant vs. moisture content (S. Laurens et al., 2003)

2.7.2 Laboratory testing

2.7.2.1 Outline

In order to measure the dielectric constant of concrete, a SPOT, which is a ground-coupled GPR unit, was used. SPOT adapts an antenna with 1 GHz frequency and wireless connection with a laptop and it can detect the dielectric constant at the surface region of concrete. Fig. 2.40 shows the dielectric measurement with SPOT on the reference plate.

Figure 2.40: GPR unit (SPOT) with reference metal plate

To investigate the correlation between moisture content and the dielectric constant, a laboratory test was conducted. A concrete panel was fabricated and relative humidity sensors were embedded. SHT75s were used to measure the internal relative humidity in concrete (Grasley et al., 2005) and they were installed at different depths from the surface of the panel (Fig. 2.41). Fig. 2.42 shows the panel specimen that was cured in the environmental chamber in which the temperature and relative humidity were maintained to 73 °F and 50 percent, respectively.

Figure 2.41: Concrete panel with relative humidity sensor

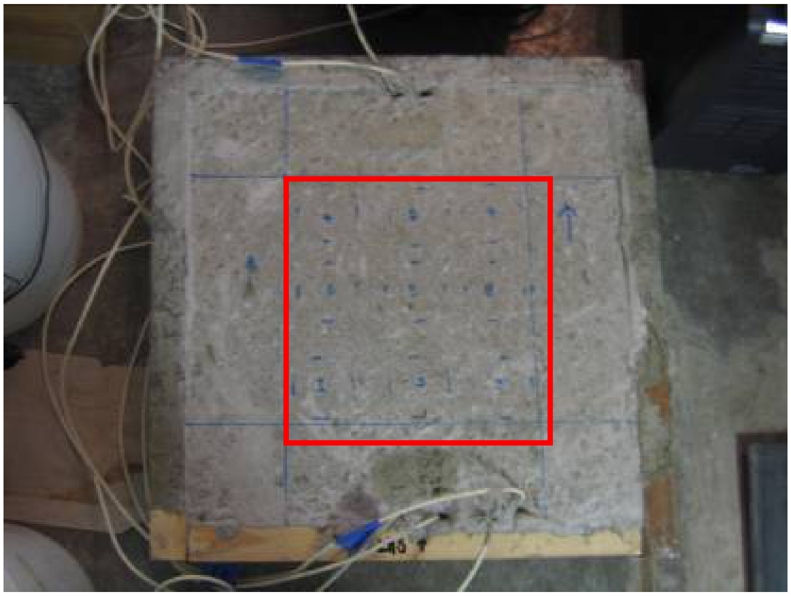


Figure 2.42: Concrete panel specimen in the environmental chamber

2.7.2.2 Relative humidity

Fig. 2.43 shows the measured internal RH at depths of 0.5, 1.0 and 1.5 inch from the concrete panel surface. Compared to the hygrochron, SHT75 produced the values of RH in the appropriate range. As expected, RH in fresh concrete was initially close to the saturated condition and decreased as the hardening of the concrete progressed. Moisture loss occurs more at the surface region than the inner region. For example, the values of internal RH were 85 percent and 94 percent at depths of 0.5 inch and 1.5 inch, respectively, when the concrete age was 2 days.

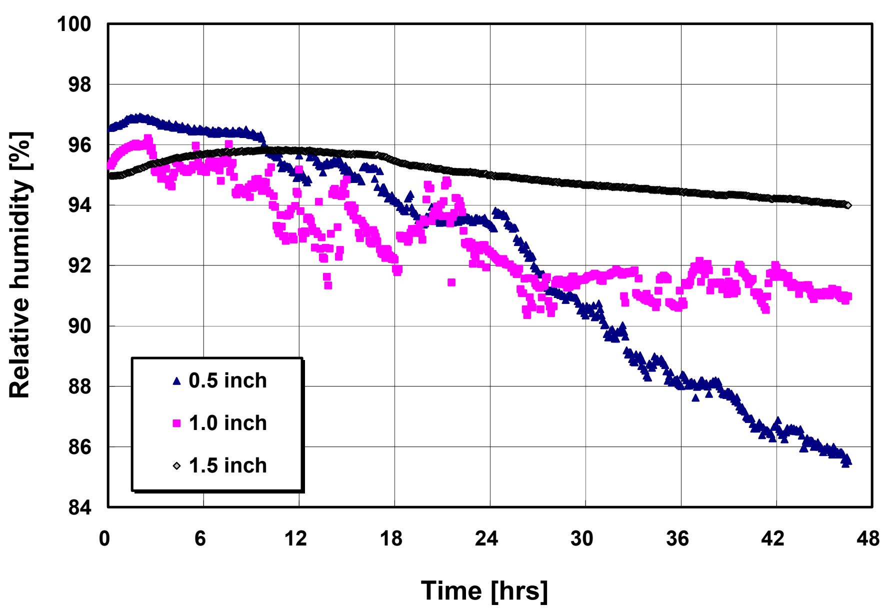


Figure 2.43: Measured internal relative humidity

2.7.2.3 Dielectric constant (DC)

The SPOT was placed at the center of the concrete panel surface to minimize the undesirable effect of edge on the dielectric constant. The red square line marked in Fig. 2.42 represents the measured area of the specimen by SPOT. The first measurement of the dielectric constant was conducted at 18 hours after the placement of the concrete and then continued at every 90-minute interval.

Fig. 2.44 shows the measured DC with the variation of RH. The dielectric constant increased with decreases of RH. The correlation between DC and RH, however, did not seem good. One of the reasons for this poor correlation is that the penetration depth of the GPR unit depends on the frequency of the antenna and stiffness of the concrete panel. The measured dielectric constant may be affected by the fast hydration process of concrete at early ages. Another reason is due to the accuracy of SPOT. The DC varied even though SPOT was placed on the reference plate. The dielectric constant may not be sensitive enough to measure the curing effectiveness due to its low accuracy.

As described earlier, a lot of techniques for the measurement of internal RH have been tried and they are still under progress. It is considered that a more reliable measurement technique on RH is prerequisite on the development of the relationship between DC and RH.

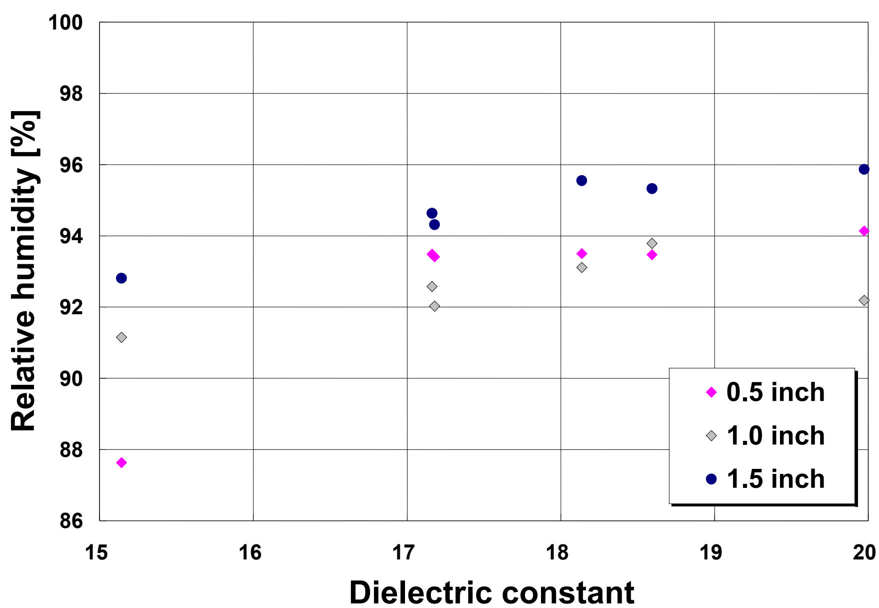


Figure 2.44: Dielectric constant vs. relative humidity

2.7.3 Field testing

To investigate the curing effectiveness with the dielectric constant, field testing was conducted at US 59 in Houston. As shown in Fig. 2.45, SPOT was used to measure the dielectric constants on new concrete pavement that was constructed at night on August 2, 2007.

Fig. 2.46 shows the measured dielectric constant in the next day. Dielectric constants diminished with time and showed different values at the different locations. Surface evaporation was considered to result in this drop. Additionally, hydration, which leads to the self-desiccation and hardening of concrete, may contribute to this drop. Compared to interior point No. 1 and No. 2, the DC at the construction joint decreased more than interior points because the exposed surface area of the concrete and the corresponding moisture loss increased. Two DCs in the interior area of the pavement showed a considerable variability. The sensitivity of DC may not be enough to differentiate the curing effectiveness. Furthermore, the GPR unit needs to be improved, especially in the aspect of accuracy.

Figure 2.45: Field measurement on dielectric constant with SPOT

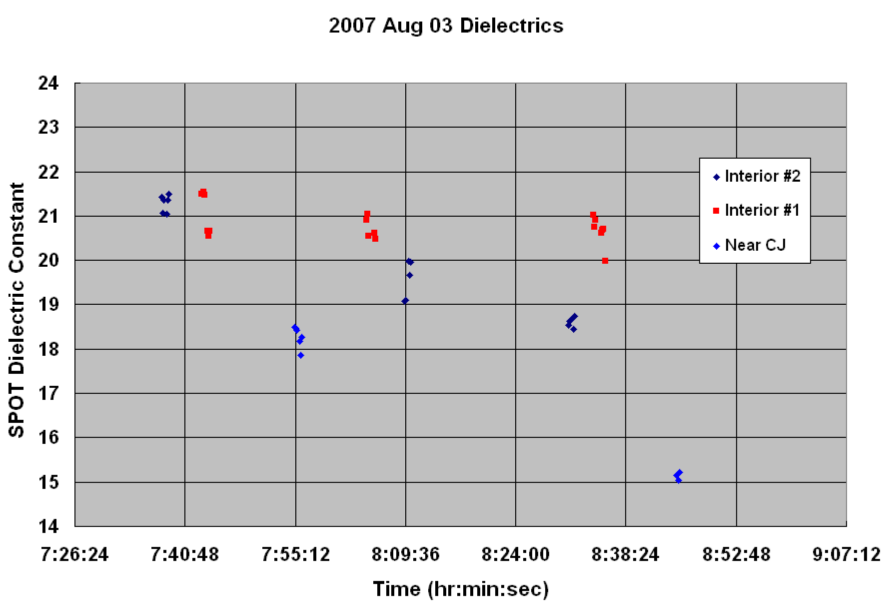


Figure 2.46: Dielectric constant vs. time in field

2.7.4 Limitation of dielectric constant measurement

Dielectric constant, which is defined as the ratio of the permittivity of a substance to the permittivity of free space, is known to have, theoretically, a close correlation with the moisture content in concrete. However, the penetration depth of wave in the GPR unit depends on the frequency of wave as well as the stiffness of the concrete. The hardening process develops very fast in early age concrete and thus the stiffness changes quickly. The evolution of stiffness may change the penetration depth and thus affect the measured DC. This change may be able to produce inconsistent results of DC.

Another issue is the sensitivity of the DC. The variation of the DC caused by moisture change is very small and it is doubtful whether the DC measurement may be able to detect the curing effectiveness accurately. Even though the GPR unit was placed on the reference plate, the DC varied. The variation cannot be neglected considering small variation of the DC caused by the change of moisture content. To apply the GPR unit to field compliance testing for curing effectiveness, its accuracy needs to be improved. Therefore, the measurement of the DC may not be a simple and easy-to-use compliance testing procedure for curing effectiveness.

3. CONCLUSIONS

3.1 CONCLUSIONS

Curing has substantial effects on the long-term performance of Portland cement concrete (PCC) pavement. TxDOT requires two applications of curing compounds, with a maximum 180 sf/gal per each application. However, no compliance testing is conducted for curing and, from a practical standpoint, compliance with specification requirements are rarely verified. The purpose of this research was to identify simple testing procedures that can be implemented to verify the compliance with specification requirements on curing. To this end, various test methods that appear to have potential for compliance testing for curing were evaluated in the field. A factorial experiment was set up for field testing, and the test methods evaluated in the field. Varying rate of curing compound applications as well as application time was included as variables in the factorial experiment. Advantages and limitations of each method were identified. Based on the findings in this research, the following conclusions are made.

1. Because the probe of the Windsor probe system is relatively small, the penetration depth is significantly affected by whether it hits coarse aggregate or mortar. The variations in penetration depth due to whether it hits coarse aggregate or mortar could be more than those affected by curing effectiveness. Additionally, substantial error could occur if the probe doesn't penetrate perpendicularly to the surface of the concrete pavement.

2. Surface temperature may detect the difference in the loss of evaporation heat which is caused by varying degrees of curing effectiveness. However, surface temperature also varies depending on weather conditions during construction. It may not be feasible to evaluate the curing effectiveness solely based on surface temperature.

3. The test on initial surface absorption is not simple and easy to implement due to the difficulty in sealing the interface between the instrument and concrete surface.

4. Reflectance has a potential for the field compliance testing to identify the application rate of the curing compound. However, it requires further advancements in this technique to make this approach feasible in the field.

5. The technology for the measurement of internal relative humidity of early age concrete is still under progress and various types of humidity sensors have been tried. In order to obtain the accurate RH in the fresh concrete, there are still a lot of improvements to be made. It is considered that, at this point in time, measurement of RH may not be a practical field compliance testing method for curing effectiveness.

6. Dielectric constant of concrete constantly changes in fresh concrete as water evaporates from the concrete. The accuracy of dielectric constant measurement

techniques currently available is not accurate enough to be included in the specifications as compliance testing.

Based on the findings above, it is concluded that the methods evaluated in this research study are neither practical nor accurate enough to be included in TxDOT specifications as a compliance testing. Based on the research effort in this study, the following potential implementation is recommended.

3.2 POTENTIAL IMPLEMENTATION

One practical issue in the curing operation is to ensure that sufficient amounts of curing compounds are applied uniformly. Currently, there is no good compliance testing available that enables TxDOT to accurately estimate the application rate of the curing compound and its uniformity. It is difficult to keep track of how much curing compound is applied. The rate of the curing compound application and its uniformity primarily depend on cart speed, pump pressure, and nozzle spacing. Retrofit of a curing machine with hardware for speed and pressure measurements may improve the current curing operation and eventually the curing effectiveness in concrete pavement.

References

ACI 228.1R-03, In-Place Methods to Estimate Concrete Strength, Manual of Concrete Practice, Part 2 Farmington Hills, American Concrete Institute, 2003

ACI 308R-01, Guide to curing concrete, Manual of Concrete Practice, Part 2 Farmington Hills, American Concrete Institute, 2001

ASTM E 1347-06, Standard Test Method for Color and Color-Difference Measurement by Tristimulus Colorimetry, 5 pp., 2006

Cather, R., "How to Get Better Curing," Concrete, The Journal of the Concrete Society, V. 26, No. 5, pp. 22-25, 1992

Grasley Z.C., Lange D.A. and D' Ambrosia M.D., Drying stresses and internal relative humidity in concrete, in Materials Science of Concrete VII, (J. Skalny, American Ceramic Society), 2005

Grasley Z.C., Lange D.A. D' Ambrosia M.D, and Villalobos-Chapa S., Relative Humidity in Concrete, Concrete International, pp. 51-57, Oct. 2006

Laurens S., Balayssac J.P., Rhazi J., Klysz G., and Arliguie G., BB 85-CD International Symposium, Non-Destructive Testing in Civil Engineering (NDT-CE), Berlin, September 16-19, 2003

Neville, A. M., Properties of Concrete, 4th edition, John Wiley and Sons, New York, 1996

Olliver, J. P., M. Massat, and L. Parrot, Parameters influencing Transport Characteristics, Performance Criteria for Concrete Durability, Kropp, J., and H. K. Hilsdorf, eds., Rilem Report 12, pp. 33-96, E&FN Spon, London, 1995

Vandenbossche J. M., A Review of the Curing Compounds and Application Techniques Used by the Minnesota Department of Transportation for Concrete Pavements, Minnesota Department of Transportation, 23 pp., 1995

Ye D., Zollinger D., Choi S., and Won M., Literature review of curing in Portland cement concrete pavement, Research Report 0-5106-1, Center for Transportation Research, 68 pp., 2005

Appendix A

2004 Specifications

SPECIAL PROVISION
360---XXX

Concrete Pavement

For this project, Item 360, "Concrete Pavement," of the Standard Specifications, is hereby amended with respect to the clauses cited below, and no other clauses or requirements of this Item are waived or changed hereby.

Article 360.3. Equipment, Section E. Curing Equipment. Second sentence is voided and replaced by the following:

Provide equipment and controls that maintain the required uniform rate of application over the entire paving area, and that are capable of electronically recording time, GPS coordinates of the curing cart, curing membrane pressure, and curing cart speed at every 10 seconds. Provide equipment with a simple gage on the control panel that clearly displays the acceptable limits of curing application rates.

Article 360.4. Construction, Section I. Curing, Section 1. Membrane Curing is supplemented by the following:

At the end of each day, provide an electronic copy of the curing record to the Engineer for the identification of areas of deficient curing where the rate of curing compound application is less than specified. Apply additional curing compounds at locations as directed by the Engineer on the same day and when the operation is completed, provide the curing record to the Engineer.