REDUCING CURLING FROM DRYING SHRINKAGE OF CONCRETE PAVEMENTS THROUGH THE USE OF DIFFERENT CURING TECHNIQUES

By

AMIR HAJIBABAEE BANA

Bachelor of Science in Civil Engineering

University of Tehran

Tehran, Iran

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REDUCING CURLING OF CONCRETE PAVEMENTS

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Thesis Approved:

Dr. M.Tyler Ley

Thesis Adviser

Dr. Bruce W. Russell

Dr. Stephen A. Cross

Dr. Sheryl A. Tucker

Dean of the Graduate College

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CHAPTER I

INTRODUCTION

1.1 OVERVIEW

Reducing the deformation in concrete pavements through the use of curing at early ages is the main concern of this study. Curing techniques achieve this by reducing the early age shrinkage, moisture gradient, and temperature differential. In this project, supported by the Oklahoma Department of Transportation (ODOT), results from the curling of the paste and concrete beams and the effects of curing techniques on them will be discussed separately. The concrete beam is a better experimental modeling of what is happening in the field; however, they are more expensive and take much more time to complete compared to paste beams. Each one of the experiments has its own advantages and may ultimately contribute to a better understanding of how different methods of curing impact curling and warping in slabs.

Chapters two and three in this thesis were written in a journal paper format to ease future publishing. Chapter two is centered on the effectiveness of wet curing and how it changes the moisture gradient and surface properties, causing a higher curling deflection. Chapter three will consider the efficiency of the curing compounds in reducing the moisture loss and curling deflections. Each chapter starts with a brief review of the recent works and continues with methods, results, discussions, and finally the chapter's conclusion. Chapter 4 concludes the thesis and will suggest some key points to have a better selection of appropriate curing methods on ODOT pavements.

CHAPTER II

THE IMPACT OF WET AND SEALED CURING TECHNIQUES ON CURLING FROM DRYING SHRINKAGE

2.1 INTRODUCTION

The performance of the wet curing methods with different curing time is the focus of the present chapter.

The purpose of curing is to maintain adequate moisture content and temperature in concrete for a period of time immediately after placing and finishing in order to develop the desired properties. Proper curing can increase durability, strength, water-tightness, abrasion resistance, volume stability, and resistance to freezing and thawing and deicers; therefore, the exposed slab surfaces are significantly sensitive to curing. The improvement in concrete properties is rapid at early ages but continues more slowly thereafter for an indefinite period (Kosmatka, Kerkhoff, Panarese 2003).

Wet curing methods maintain the presence of mixing water and saturation in the concrete during early ages. Wet curing methods include ponding, fogging, and saturated wet coverings. These methods afford some cooling through evaporation, which can be beneficial in hot weather. Fabric coverings saturated with water, such as burlap, cotton mats, rugs and etc. are commonly used for curing.

The early age period in the life of concrete is approximately the first seven days after final set. Concrete properties change rapidly at early ages. Change in properties continues more slowly thereafter. Rapid and large moisture loss from the surface of a slab can reduce the degree of hydration. Also, harmful consequences like plastic shrinkage cracking, and decreases in strength, durability, and abrasion resistance can occur without precautionary curing. Some amount of curling is expected on every pavement project (ACI 302.1R). For the large moisture loss at the top layers, the difference in moisture content results in more drying shrinkage at the top than the bottom causing the slab to curl upward at the edges as shown in Figure 2 - 1 (Ytterberg 1987, Parts I, II, III). If the concrete is restrained, either internally or externally, restraint may cause the concrete to crack due to drying shrinkage.

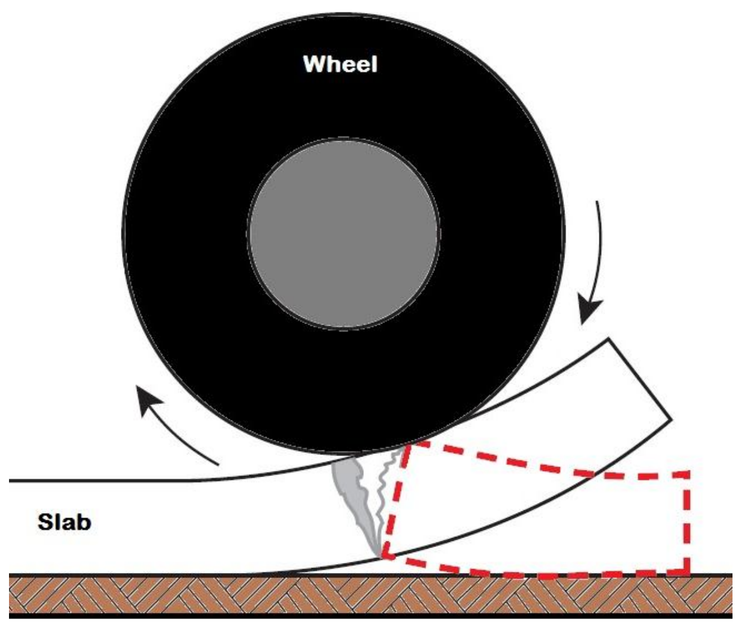

Figure 2 - 1: Warped slab cracks under the heavy wheel loading (Kosmatka et al 2003)

The amount and type of curing can affect the rate and ultimate amount of drying shrinkage. Wet curing methods, such as fogging or wet burlap, hold off shrinkage until curing is terminated, after which the concrete dries and shrinks at a normal rate (Kosmatka et al 2003). The slab starts drying and shrinking immediately after the termination of the curing if the concrete has been kept continuously moist since casting and finishing. The moisture distribution in a hardened slab is assumed to be uniform before drying begins (Hanson 1968) and it starts changing as concrete loses moisture (Hedenblad 1997). Depending on the length of the drying period, drying conditions, and the initial water content, the RH at equilibrium varies (Hedenblad 1997). To avoid or lessen this moisture gradient, the top and the bottom of the slabs should be uniformly kept moist or dry. For points deeper within the concrete the drying time will increase to reach to a certain RH (Monfore 1963), and curing for longer than one day will significantly add to the drying time (Hedenblad 1997).

The drying shrinkage of the cement paste is six to eight times greater than amount observed in concrete (Bisschop 2002). The paste shrinks about 1.7 times more than mortar (Holt 2002). The shrinkage can be decreased by reducing the paste content, adding aggregate content (Tazawa et al. 1995), and increasing the maximum aggregate size. The impact of fly ash was found to either have no impact or increase the shrinkage of a mixture (Setter and Roy 1978; Justnes et al, 1998). Air content less than 8% was found to not influence shrinkage (Davis and Troxell 1954). So the shrinkage of the concrete (S_C) is highly affected by the shrinkage of the cement paste (S_P) and aggregate volumetric fraction (g) because the aggregate restrains the shrinkage of the cement paste in the concrete (Pickett 1956):

Equation 2 - 1 : $$S_C = S_P (1 - g)^n$$

The capillary forces during drying are generally the reason for shrinkage (Lane, Scott, and Weyers 1997). The drying shrinkage in cement paste is caused by a negative pressure called capillary tension (P_{cap}) inside the liquid phase after formation of menisci (curved liquid-vapor interfaces); so shrinkage of paste (S_P) can be defined as a function of capillary tension (P_{cap}), degree of saturation of cement paste (S), bulk modulus of paste (K), and modulus of solid skeleton inside cement paste (K_s) (Mackenzie 1950; Bentz et al.1998):

$$\text{Equation 2 - 2:}\quad S_P = \frac{S}{3} P_{cap}\left(\frac{1}{K} - \frac{1}{K_s}\right)$$

Due to the generation of the hydration products in the cement matrix, autogenous shrinkage occurs; this component may be more important for concrete mixtures with w/c less than 0.40 (Tazawa 1999). The autogenous shrinkage will increase by reducing the w/cm and increasing the cement fineness since the capillary tension mechanism will cause higher tension in the pore water of the finer structure (Bentz et al. 2001a, Jensen and Hansen 1996). Also, due to the smaller volume of the hydration products than that of the reactants, there is an approximately 8% to 9% reduction in volume after hydration reactions called chemical shrinkage (Jensen and Hansen 2001). Due to lack of water, concrete sealed against moisture loss with w/c < 0.5 cannot progress to its complete potential hydration (Powers, 1948). Concrete with w/c < 0.4 can dry itself from inside (Powers 1948; Mills 1966; Cather 1994; Meeks and Carino 1999). Due to low permeability at those low w/c ratios, the curing water does not infiltrate away from the surface (Cather 1994; Meeks and Carino 1999). This layer of the concrete is highly affected by the curing water (Cather, 1992), which continues to a depth of approximately 1/4" to 3/4" depending on the concrete characteristics (Carrier 1983; Spears 1983). The lower permeability of the concrete causes the slower moisture movement between the cured surface and the interior (Pihlajavaara 1964, 1965).

The formation of the menisci occurs in external drying as well; the specimen suffers from both external drying at the exposed surface and internal drying (self-desiccation) in an unsealed specimen. The radius of these menisci is reduced as moisture evaporates, and the internal RH of the cement paste decreases until the internal RH reaches the ambient RH, or equilibrium

(Radlinska et al. 2008). The formation of the menisci and generation of the capillary tension (P_{cap}) can be related, according to the Laplace equation, if γ is surface tension of pore fluid, θ is the liquid-solid contact angle, and r is the radius of the curvature of the meniscus (Adamson and Gast 1997):

Equation 2 - 3: $$P_{cap} = -\frac{2\gamma \cos(\theta)}{r}$$

The solid surfaces or pore walls will be pulled together by this negative pressure, causing the volume change or shrinkage. The capillary tension is also related to the RH of the cement paste by the Kelvin equation (Adamson and Gast 1997):

Equation 2 - 4: $$P_{cap} = \frac{RT \ln(RH)}{V_m}$$

Where R is the universal gas constant, T is the temperature and RH is the internal relative humidity, and V_m is the molar volume of pore solution.

Drying shrinkage may be increased by curing longer than 4 to 8 days and less than 35 to 50 days (Perenchio 1997). The shorter curing time will result in a faster drying rate (Hedenblad 1997; Jackson and Kellerman 1939). Wet curing for 28 days increases the time needed to reach a certain RH by approximately 1 month (Hedenblad 1997). During the first day of drying, the concrete and cement paste reach the peak tensile stress in the surface, resulting in surface micro-cracking (Hwang and Young 1984; Higgins and Bailey 1976); this could be even faster for cement paste within 1 minute after exposure (Higgins and Bailey 1976). Slabs should not be cured by adding water like wet burlap and should be protected from any external water if drying time is critical (ACI 302.2R-06).

The drying shrinkage and curling may get worse by using a vapor barrier immediately under the concrete; the slab loses little or no water from the bottom, while the top dries and shrinks at a faster rate (Anderson and Roper 1977, Nicholson 1981, Turenne 1978). Installing an impervious membrane like vapor/moisture barrier below the slab makes maintaining the moisture at the top of the slab highly essential to minimize curling. Therefore, ACI 302.1R suggests placing a 4 in. drainable, compressed fill on top of the vapor barriers to minimize this moisture gradient and to consequently decrease the curling. Also, for avoiding or minimizing this problem after curing, the wet burlap should be replaced with a plastic sheet until the concrete surface has become dry under the sheets (ACI 308R-01). Using a sheeting material to cure for 3 days is recommended (Suprenant and Malisch 1999c). Installing a floor covering causes the moisture movement from the bottom to the top of the slab; this movement will reduce the curling initially due to the expansion at the top as the moisture content there increases and the shrinkage at the bottom as the moisture content there decreases (Tarr et al. 2006). It is required by some specifiers to use the granular blotter layer to reduce the chance of curling deflection and cracking caused by plastic and drying shrinkage; unable to drain due to use of vapor barrier, the wet fill will cause extra moisture evaporation from the slab.

While it is common to recommend that concrete receive a prolonged wet cure, some previous literature suggests that this may promote drying shrinkage. In a concrete pavement one concern with a concrete pavement is differential drying shrinkage that would occur over the cross section. This would cause curling and possibly cause damage to the pavement because of loss of support. Currently in the literature there is almost no work that has been done to investigate the impact of sustained wet curing on curling. This research will attempt to provide new insights in this area.

2.2 EXPERIMENTAL INVESTIGATIONS

2.2.1 Paste beams

2.2.1.1 Materials

The Portland cement used in these tests was a type I/II, according to ASTM C 150, and its oxide analysis per ASTM C 114 and the phases' concentrations are shown in the following Table 2 - 1. The paste mixutures in this experiment had a water to cement ratio (w/c) of 0.34, 0.42, and 0.5.

Table 2 - 1: Oxide analysis of the cement used for paste beams and the phase concentrations

Chemical Test Results	
SiO_2	20.23
Al_2O_3	4.77
Fe_2O_3	3.23
CaO	64.15
Phase concentrations	
C_3S	70.69
C_2S	4.68
C_3A	7.18
C_4AF	9.83

2.2.1.2 Sample preperation and methods

The paste mixtures were prepared according to ASTM C 305 with a Hobart mixer. Three paste beams with dimensions of 39.4" x 2.4" x 0.5" were prepared in plastic molds from each mixture. After casting all specimens were cured with wet burlap for 24 hours. To avoid the moisture loss from the sides and bottom face of the beam, each beam was sealed with melted wax after demolding. Testing was also done with aluminum tape to compare the results. Little difference was found in the specimens and so the wax was used for all subsequent testing. The finished surface of the beam was exposed to different curing techniques for different durations. An overview of these specimens is shown in Figure 2 - 2. The thinner concrete members shrink faster than the thick members due to the faster drying rate; the shrinkage rate is generally assumed to be related to the ratio of the specimen's volume to its surface area (Hansen and Mattock 1966). The shape of the specimen determines the distance for water movement to the dry surface and the stress concentrations caused by the non-uniform shrinkage; the developed stresses and shrinkage strains due to the moisture gradients during drying is highly related to the specimen size (McDonald and Roper 1993; Pickett 1946; Browne 1967).

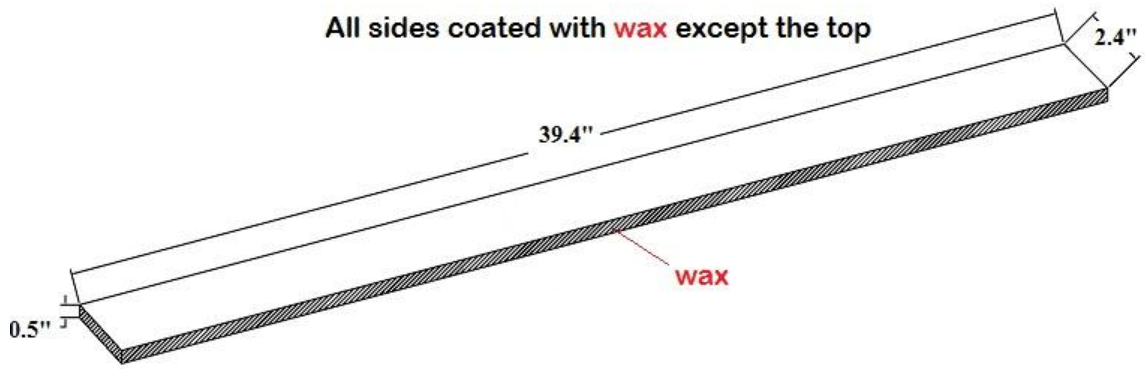

Figure 2 - 2: A waxed paste beam on all side except the finished surface

The specimens were demolded, weighed, sealed with wax, and reweighed. Finally these specimens were stored in an environmental chamber at 73˚F and 40% relative humidity. This caused a moisture gradient to form in the beam over time due to the water loss from only one side.

In this experiment since the top of the surface was not sealed with wax and water was allowed to evaporate. This differential loss of moisture in the specimen caused a moisture and shrinkage gradient in the specimen. This gradient caused differential strain to occur and results in the curling of the specimen. This test is advantageous, as the moisture loss is quick and the resulting gradients can be quite large. This leads to a significant deformation of the specimens that is easy to measure. To ensure that the curling measurements were only the result of this differential in strain caused by the drying, the beams were stored on their sides. This test is similar to previous work done by Burke (2004) to investigate the effectiveness of shrinkage reducing admixtures.

2.2.1.3 Test procedure and measurement

To measure the curling, two ends of the specimen are attached to a flat aluminum plate with the uncoated surface facing the plate, as shown in Figure 2 - 3. The distance between the aluminum plate and the specimen is measured at regular locations along the length with a caliper that reads to 0.0005". The curling of the beam is symmetric and the maximum is at the middle of the beam. The weight of the sample is also measured at different times with a scale accurate to 0.1 grams. This measurement was used to get information about the moisture content of the specimen.

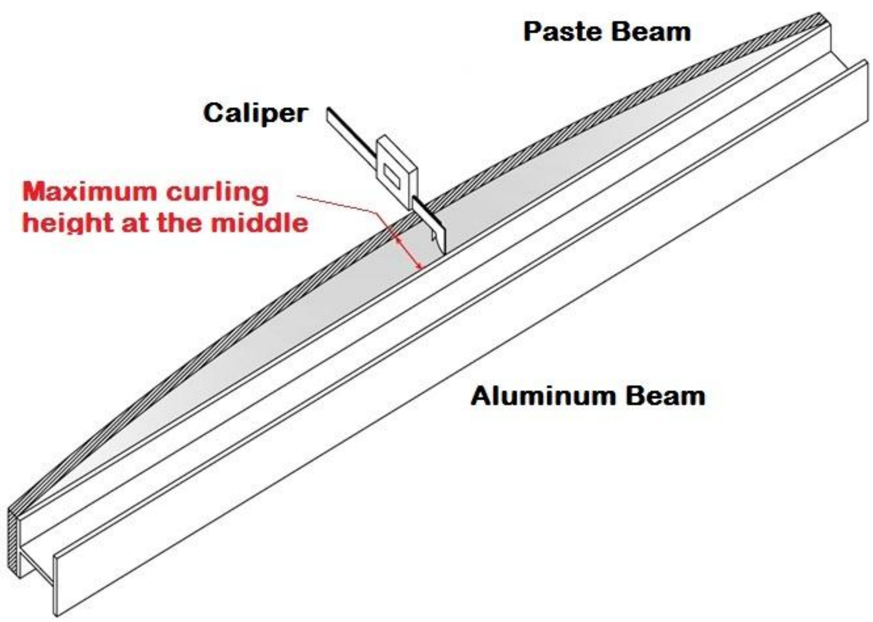

Figure 2 - 3: Measuring the curling height using a caliper

The focus of this work was to compare the performances of different durations of wet and sealed curing. All samples were wet cured at 73˚F for 1 day before demolding. This was necessary to ensure the specimens gained enough strength. Some samples were also kept in wet burlap for 1, 3, 7, and 14 days of additional curing after demolding and waxing. The curing was then removed, and the specimens were subjected to the 40% relative humidity and 73 ˚F drying environment. In addition to wet curing, several specimens were cured in a sealed plastic bag for 1 and 3 days. This curing was similar to the wet burlap cure, but no external moisture was added to the specimens during the sealed curing process. Other samples received no curing after demolding.

2.2.2 Concrete beams

2.2.2.1 Materials

The cement used in this test is type I, according to ASTM C 150, and its chemical analysis is per ASTM C 114 shown in the following Table 2 – 2 beside the phases' concentrations.

Table 2 - 2: Chemical analysis of the cement used in this project for concrete beams

Chemical Test Results	
SiO_2	21.13
Al_2O_3	4.71
Fe_2O_3	2.55
CaO	62.06
Phase concentrations	
C_3S	52.14
C_2S	20.22
C_3A	7.69
C_4AF	7.96

Samples were made with dolomitic limestone aggregate and natural river sand. An ASTM C 618 class C fly ash was also used. A wood rosin AEA was used for the first and second beams with no curing and 3 days wet curing techniques, but not for any others. During the testing it was found that it was too difficult to produce consistent air content between mixtures, and so the AEA was no longer used. The concrete beams were sealed in a similar manner to the paste beams. A moisture barrier was used as a form liner. This material had a plastic water-proof membrane on one side and fibers on the other. The fibers were oriented so that they bonded to the wet concrete and provided a tight fit of the water proof layer on the outside of the beam. The interface between the beam and the water membrane was sealed with hot glue to insure a good bond was maintained throughout the test.

2.2.2.2 Mixture Proportions and Procedures

In this experiment we used water to cement ratio equal to 0.41 for concrete beams. All of the aggregate, both coarse and fine, were charged into the mixer along with approximately two-thirds of the mixing water. The combination was mixed for three minutes. Next any clumped fine aggregate was removed from the walls of the mixer. Then the cement was loaded into the mixer, followed by the remaining mixing water. The mixer was turned on for an additional three minutes. Once this mixing period was complete, the mixture was left to "rest" for the following two minutes while the buildup of material along the walls was removed. Next the mixer was started and the admixtures were added and the mixer was allowed to run for the remainder of the three minutes (ASTM C 192). The slump (ASTM C 143), unit weight (ASTM C 138) and the air content (ASTM C 231) were measured. The typical mix proportion used in this test is presented in Table 2 - 3 for each cubic yard.

Table 2 - 3: Mixproportion used in this experiment per cubic yard

Cement (Ib)	451.2
Fly Ash (Ib)	112.8
Course aggregate (Ib)	1842.1
Fine aggregate (Ib)	1276.1
Water (Ib)	207.1

2.2.2.3 Sample preperation, Casting and Curing

In this experiment the size of the concrete specimen investigated was 7.5′×6″×8″. All sides of the beam were sealed with a synthetic moisture barrier except the top surface for each specimen. An overview of this specimen is shown in Figure 2 - 4. This specimen is similar to work done by Hansen et al. (2007) and Springerschmidt et al (2001), with some modifications.

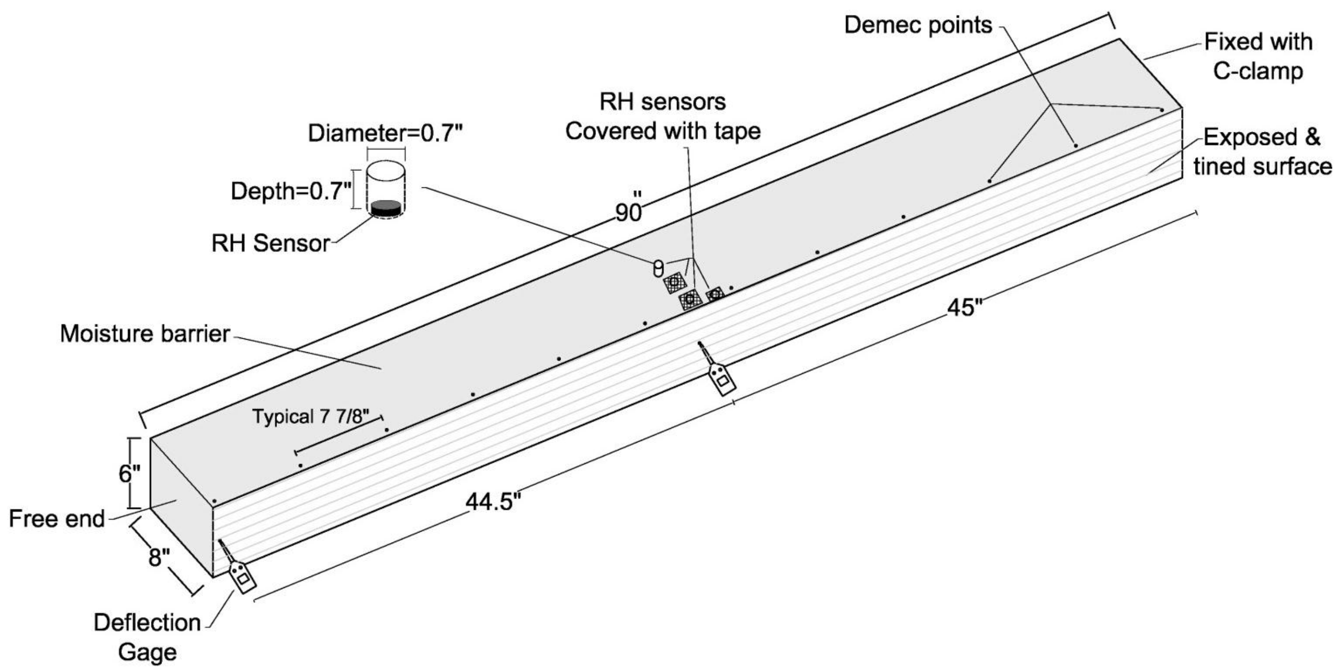

Figure 2 - 4: Concrete beam dimension and details

After placing and vibrating the concrete in 3 different layers the top surface was screeded with a piece of wood; burlap was dragged over it , and finally it was tined with a steel comb, creating tines with transverse grooves 1/16″ wide, 1/4″ deep, and with center to center spacing of 1″. These tine sizes match typical dimensions used locally. The sample was carefully demolded 5 hours after casting. Then it was sealed at the edges by wax. Specimens were prepared with no curing and 1 and 3 days of wet cure with wet burlap and a plastic tarp. The beams were flipped on their side and placed on wooden dowels after the curing was completed. This was done to minimize the influence of gravity on the results. After placing the beam on its side, it was fixed at the end with a C-clamp, steel plates, and rubber bearing pads in an environmental chamber at 73˚ F temperature and 40% relative humidity.

2.2.2.4 Test Procedure and Measurement

The relative humidity was measured at 0.5″, 1″, 3″, and 5″ from the finished surface by using the DS1923 Hygrochron Temperature/Humidity Logger iButtons. The sensors were placed in 0.7" deep holes with 0.7" diameter that were cast into the side of the concrete beam as shown in Figure 2 - 7. During demolding the forms used to make these holes were removed and the holes were covered with tape. Five days after the beam was stored on its side relative humidity gages were inserted into the beam. These sensors were programmed to take relative humidity measurements every hour. This wait period was used so that the gages did not fail due to the high amount of moisture in the beam. The holes were sealed with water poof tape after the beam was demolded. This tape was removed briefly when the sensors were added to the beam and each month when the data was obtained from the sensors.

Figure 2 - 5: Plan view of the test setup showing the holes covered by tape, deflection gauge secured to the beam, and demec points glued on the surface of the concrete.

The curling height of the beam was measured at two different locations: 45″ and 89.5″ from the end that is clamped. The accuracy of this gage was 0.0005". Also the surface strain of the beam was measured at 10 different locations, as shown in Figure 2 - 4 and Figure 2 - 5. Surface mounted stainless steel gage points were glued to the surface of the concrete beam. This was achieved by burning through the membrane in a localized area and then gluing one of these gage points. A mechanical strain gage was used to measure the movement of machined cones in points over time. The accuracy of this gage was 4 micro-strains. These measurements were taken to check the curling measurements of the beam.

2.2.2.4.1 Calibration of RH sensors

The iButton sensors were calibrated according to ASTM E 104 "Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions" with four different salt saturated solutions. The relative humidity calibration range was between 57.6% and 97.3%. This was chosen in order to cover the ranges of humidity expected in the testing. A specific calibration was generated for each iButton.

2.3 RESULTS

2.3.1 Paste Beams

A typical result for a paste beam is shown in Figure 2 - 6. This figure shows the typical curves gained by measuring the deflection of the beam at different locations over time for a sample that was not cured after demolding with a 0.5 w/c. The maximum curling is at the middle of the bar.

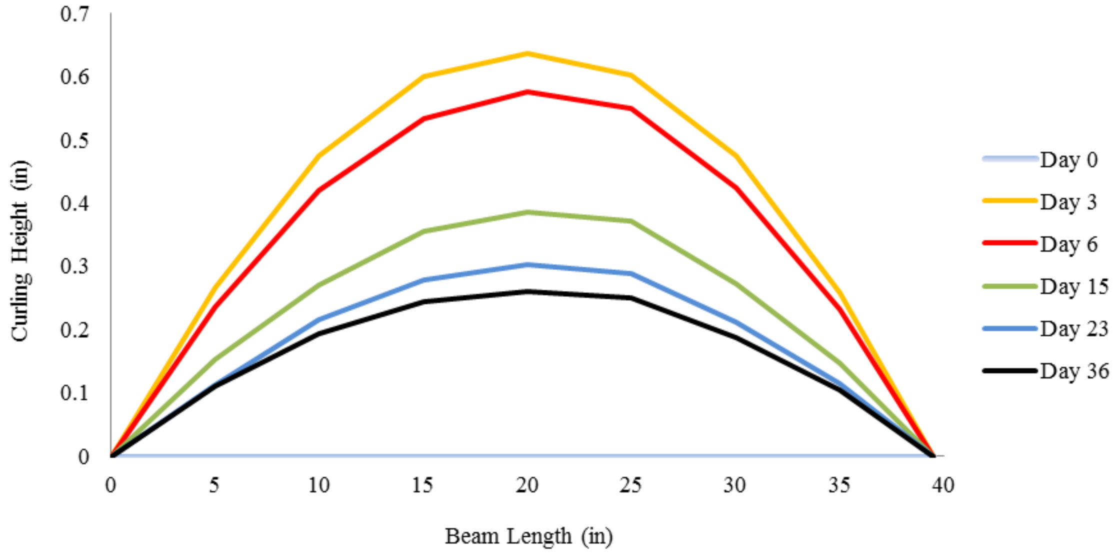

Figure 2 - 6: Curling height of a no-cured paste beam mixed with w/c=0.5

The following Figure 2 - 7 shows the change of the beam's weight after being exposed to the drying environment.

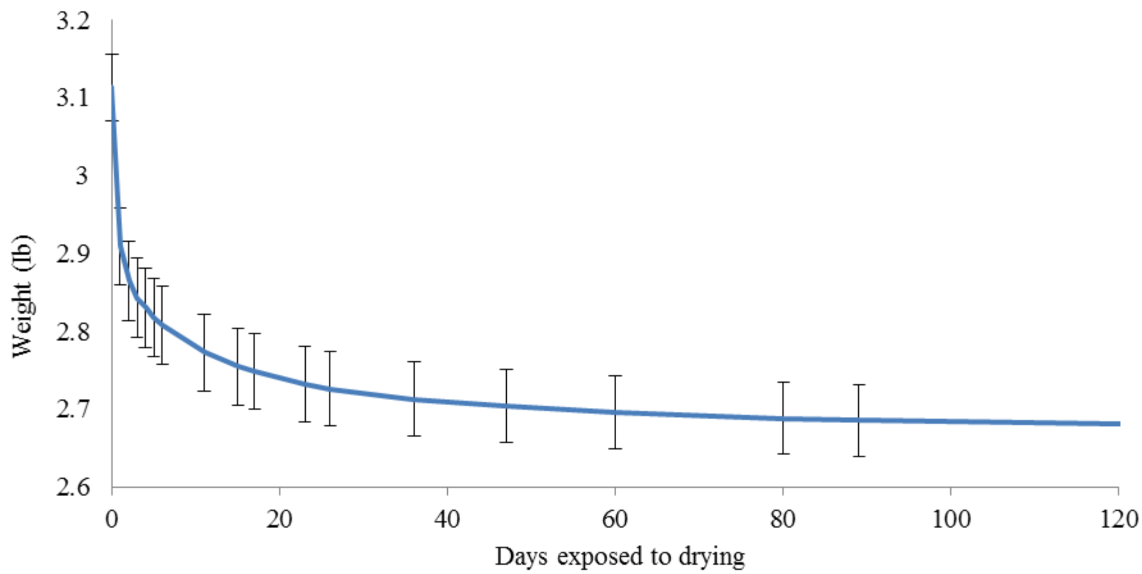

Figure 2 - 7: no-cured paste beam's weight versus age

The moisture loss and the maximum curling height of samples of w/c=0.42 cured with wet burlap for additional 1, 3, 7, and 14 days and the measurements for a no-cured specimen over the time periods are shown in Figure 2 - 8 and Figure 2 - 9 respectively. The red markers show that the maximum curling occurs at later and later ages.

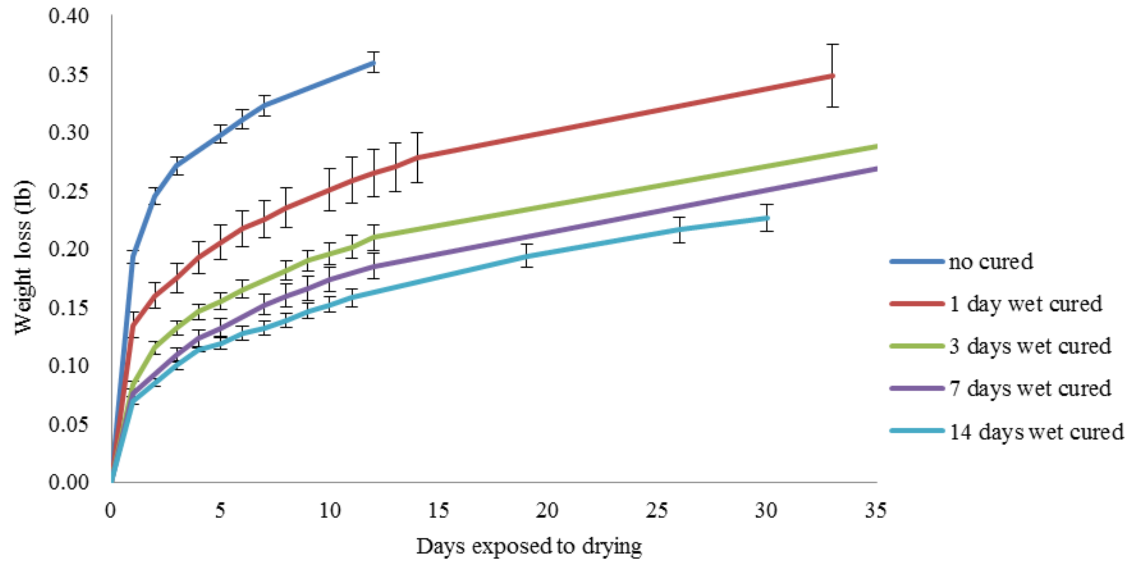

Figure 2 - 8: Weight loss over the age of the paste specimen

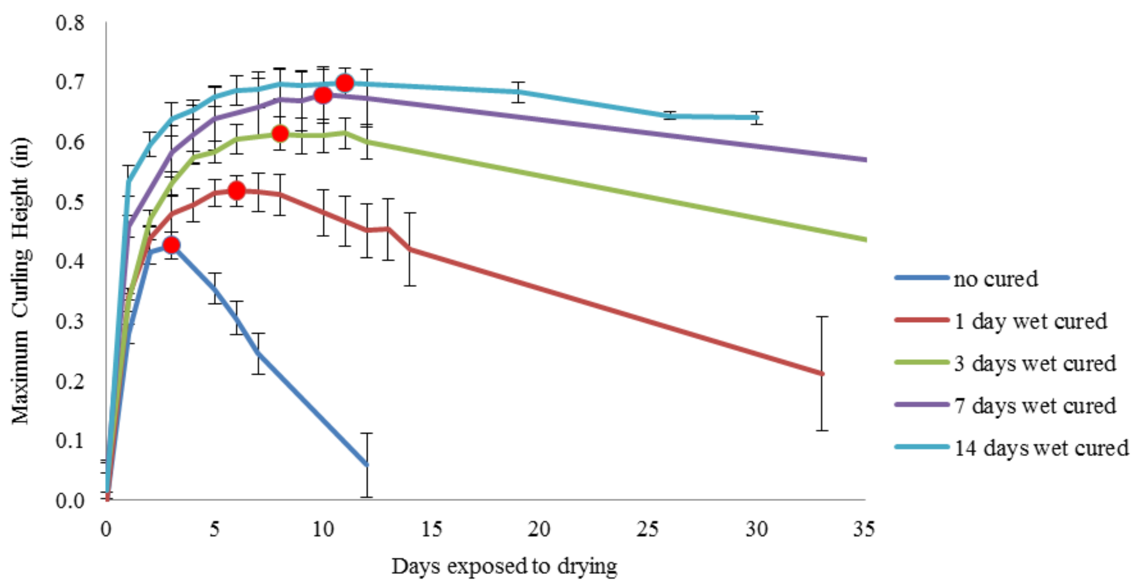

Figure 2 - 9: Paste beams' maximum curling height over the time

The moisture loss and the maximum curling height of samples with the same w/c=0.42 sealed with a plastic bag for 1 and 3 days and the measurements for a no cured specimen at the same ages are shown in Figure 2 - 10 and Figure 2 - 11 compared to specimens of 1 and 3 days of additional wet curing.

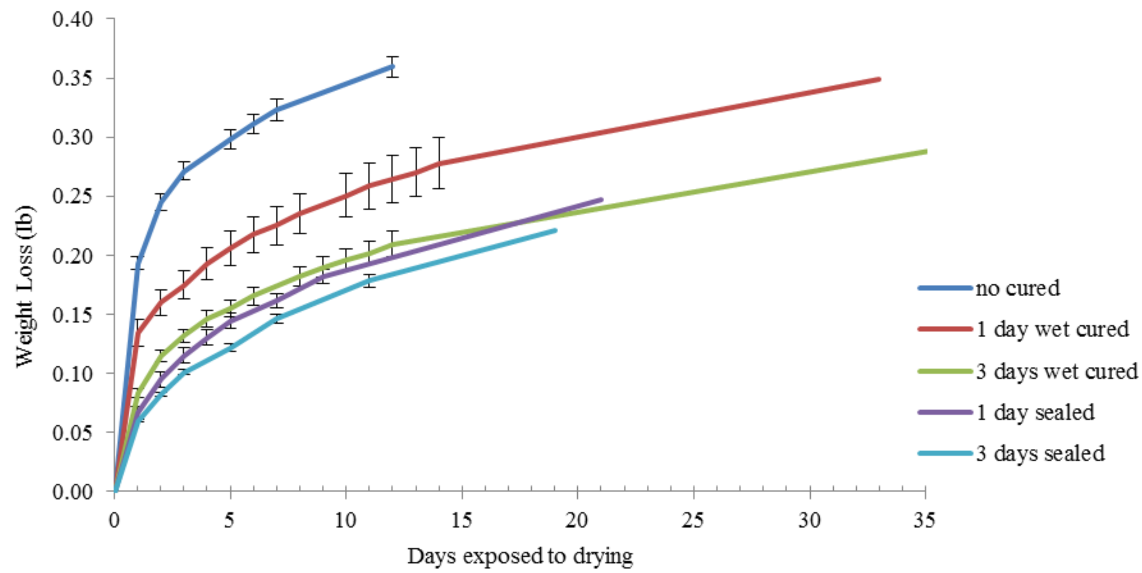

Figure 2 - 10: Weight loss over the age of the paste specimen

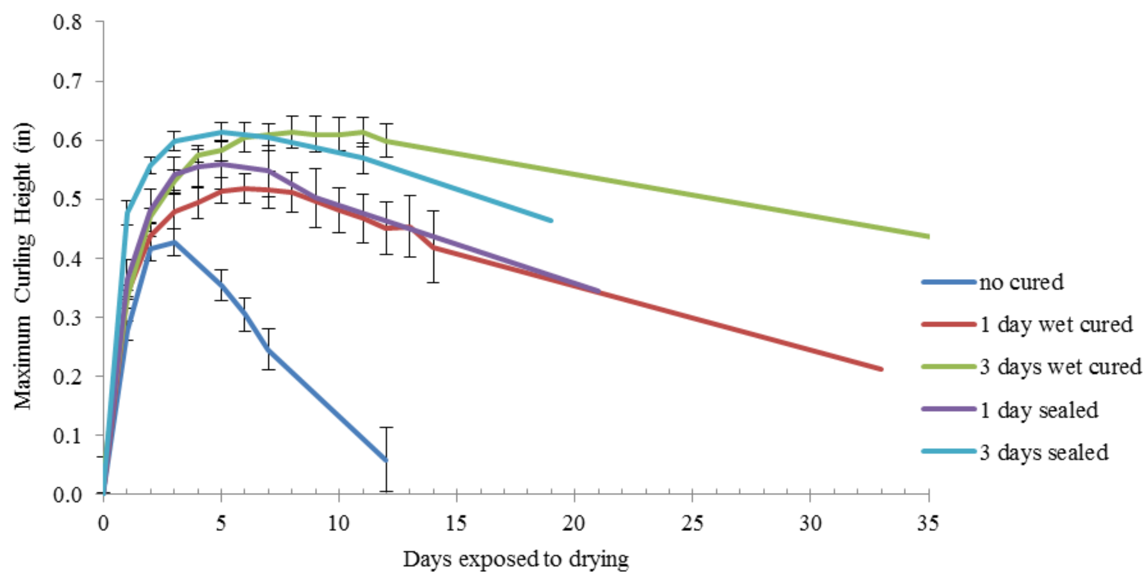

Figure 2 - 11: Paste beams' maximum curling height over the days exposed to drying

Figure 2 - 12 summarizes the response of the samples with different w/c and curing period.

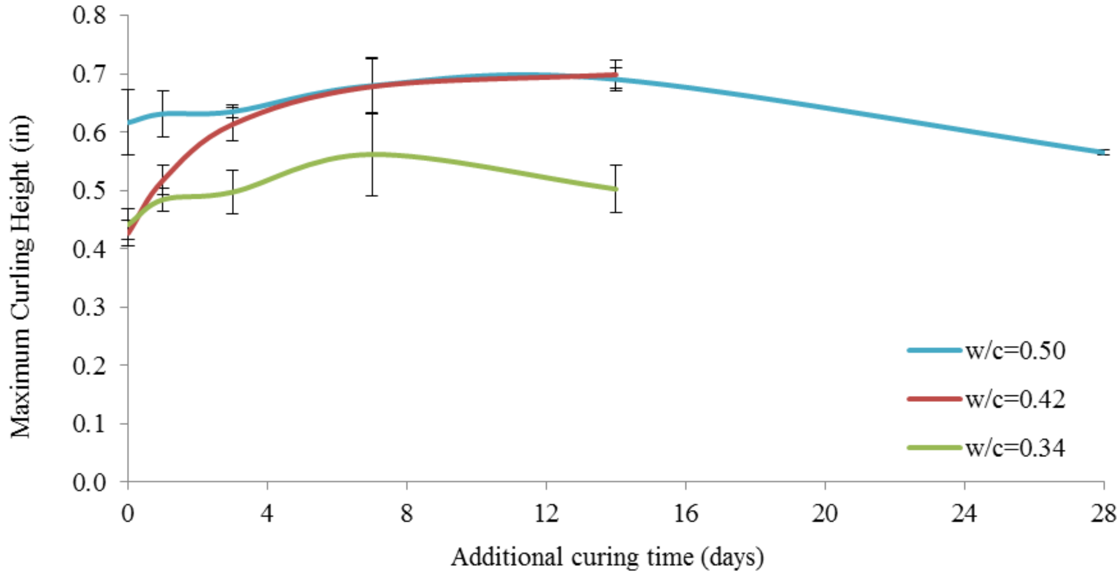

Figure 2 - 12: Comparison between the maximum deflections of paste beams with different w/c ratios

Figure 2 - 13 presents the weight loss of the specimens at maximum deflection versus curing time.

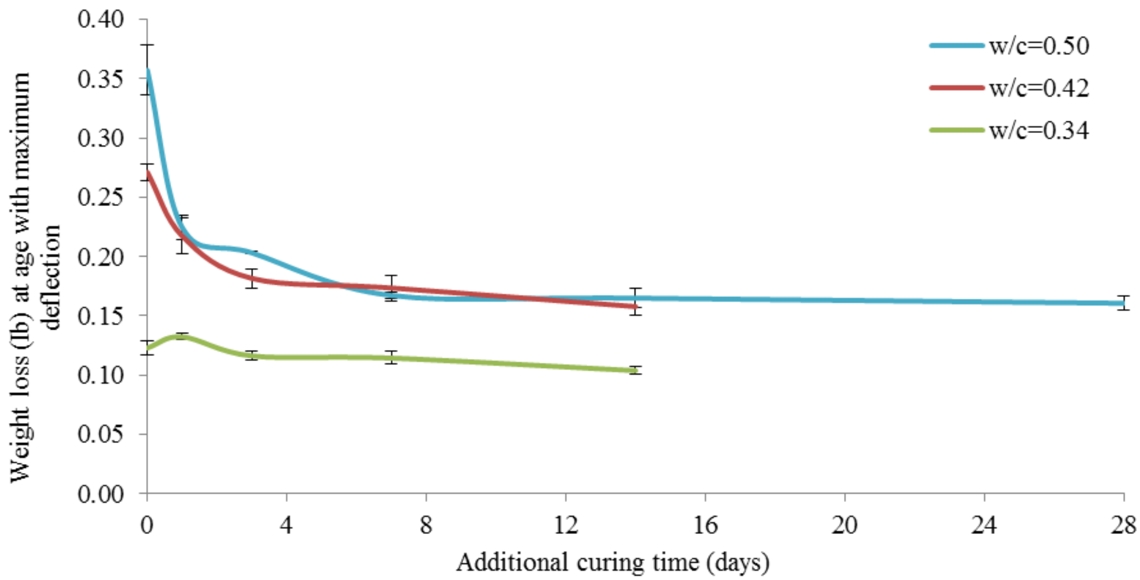

Figure 2 - 13: Weight losses of paste beams with different w/c ratios at age with maximum curling height

Figure 2 - 14 presents the weight loss after 11 days versus the additional curing time.

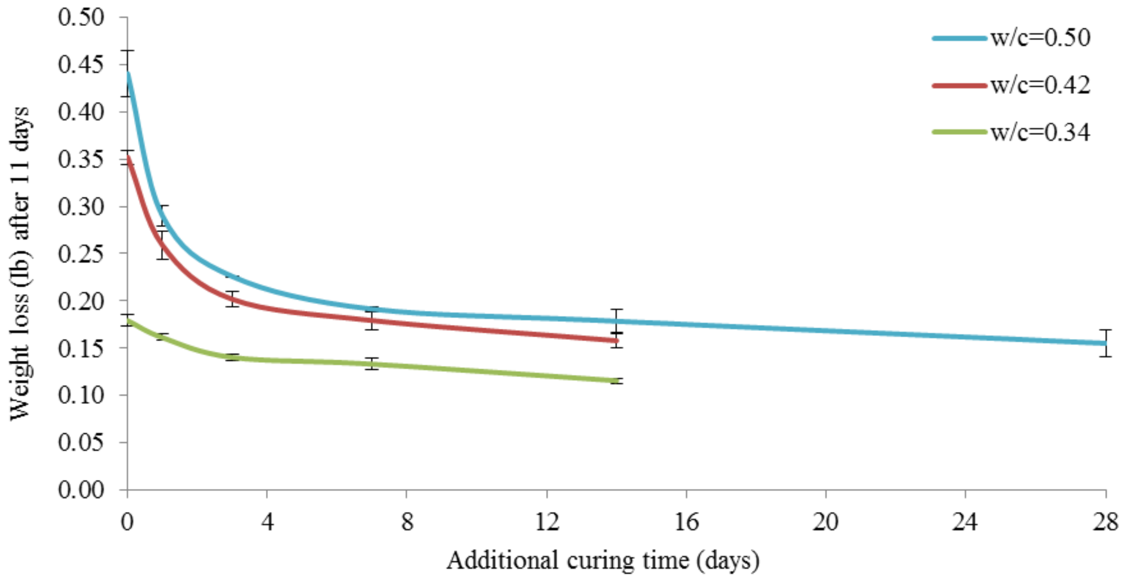

Figure 2 - 14: Weight losses of paste beams with different w/c ratios after 11 days

2.3.2 Concrete Beam

The average surface strain over the length of the beam and the tip deflection during the drying period are shown in Figures 2 - 15 and 2 - 16 for the specimens investigated. The methods used in this experiment are no-curing, 1-day wet curing, and 3-day wet curing.

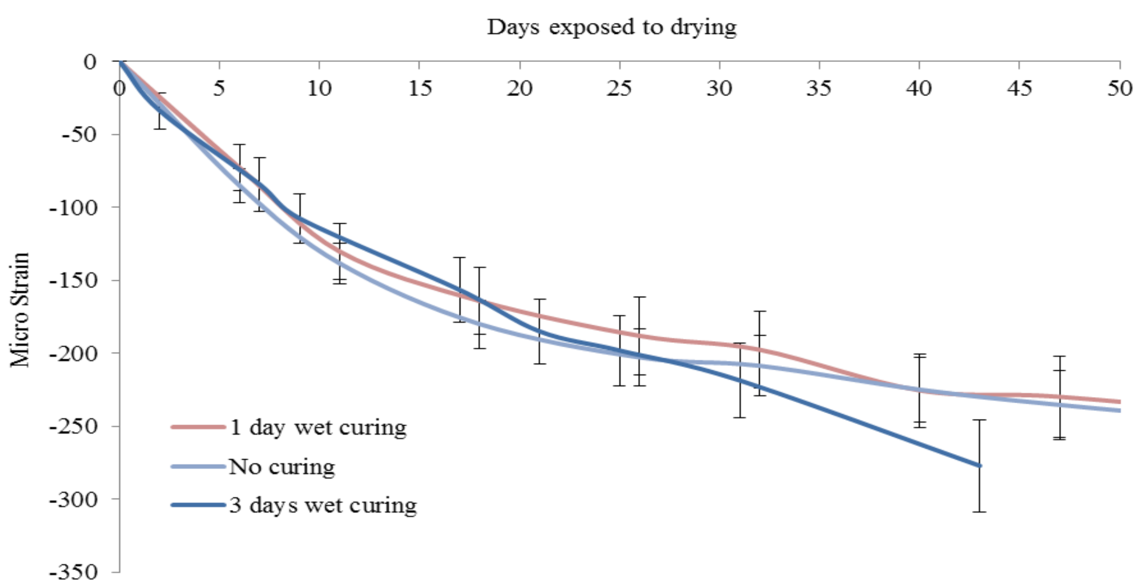

Figure 2 - 15: Average surface strain over the concrete beams' length with age

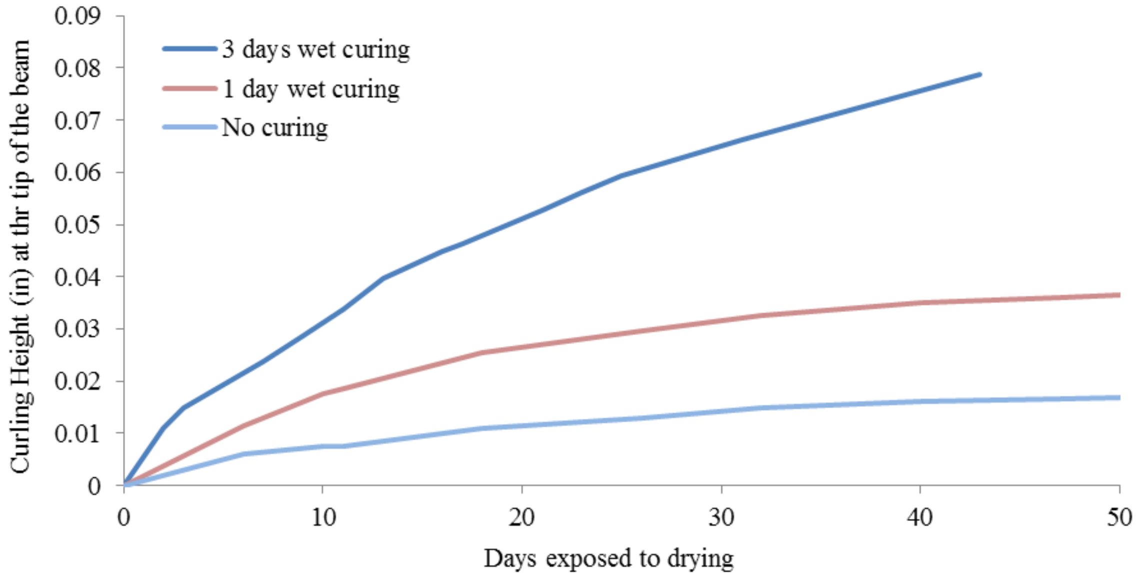

Figure 2 - 16: The tip deflection for the specimens investigated

A typical plot of the relative humidity versus the days of drying is shown for a beam that was not cured is shown in Figure 2 - 17 for different depths.

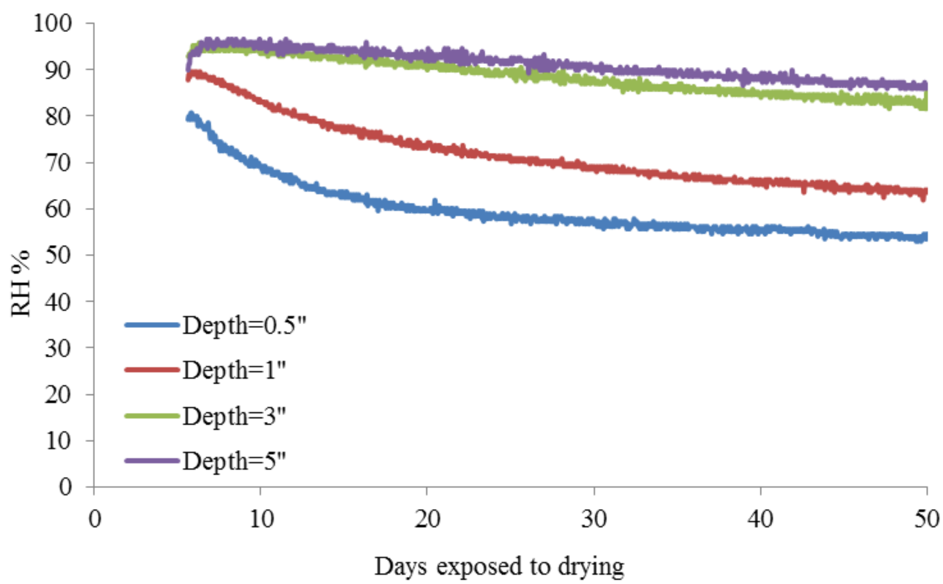

Figure 2 - 17: The relative humidity of the no curing technique in different depths over age for concrete beams

The relative humidity profiles for no-curing at 6, 15, 25, and 50 days after exposure are all shown in Figure 2 - 18.

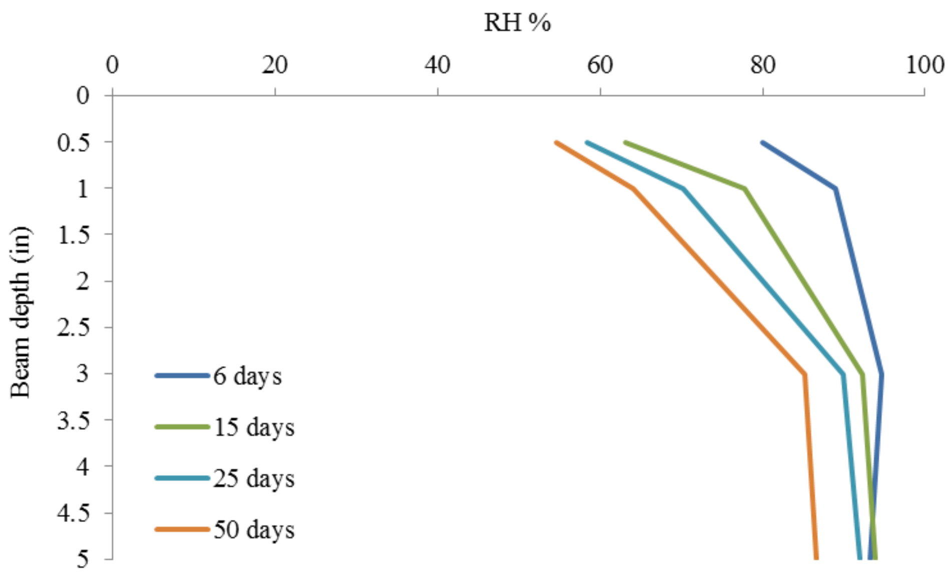

Figure 2 - 18: The RH profiles for no curing at 6, 15, 25, and 50 days after exposure for concrete beams

The relative humidity profiles for 1 day wet curing at 6, 15, 25, and 50 days are shown in Figure 2- 19.

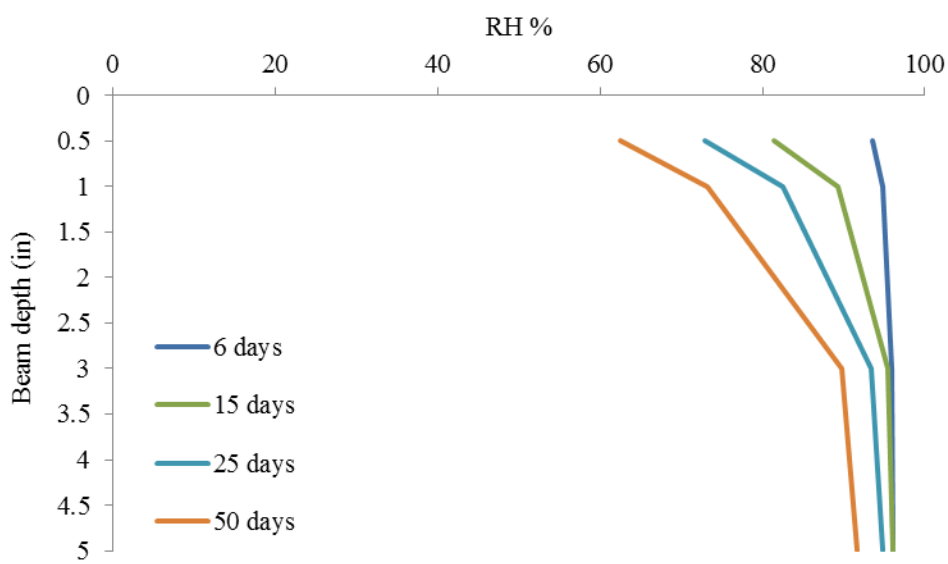

Figure 2 - 19: The RH profiles for 1 day wet curing at 6, 15, 25, and 50 days after exposure for concrete beams

The relative humidity profiles for 3 days wet curing at 8, 15, 25, and 50 days after exposure are all shown in Figure 2 - 20.

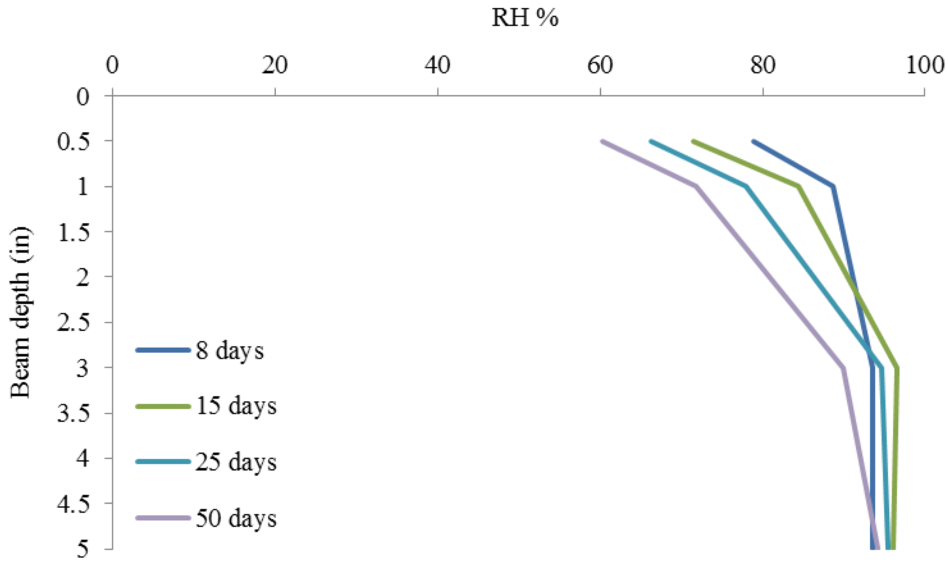

Figure 2 - 20: The RH profiles for 3 days wet curing at 8, 15, 25, and 50 days after exposure for concrete beams

The following Figure 2 - 21 shows the comparison between the RH profiles of the considered techniques after 50 days.

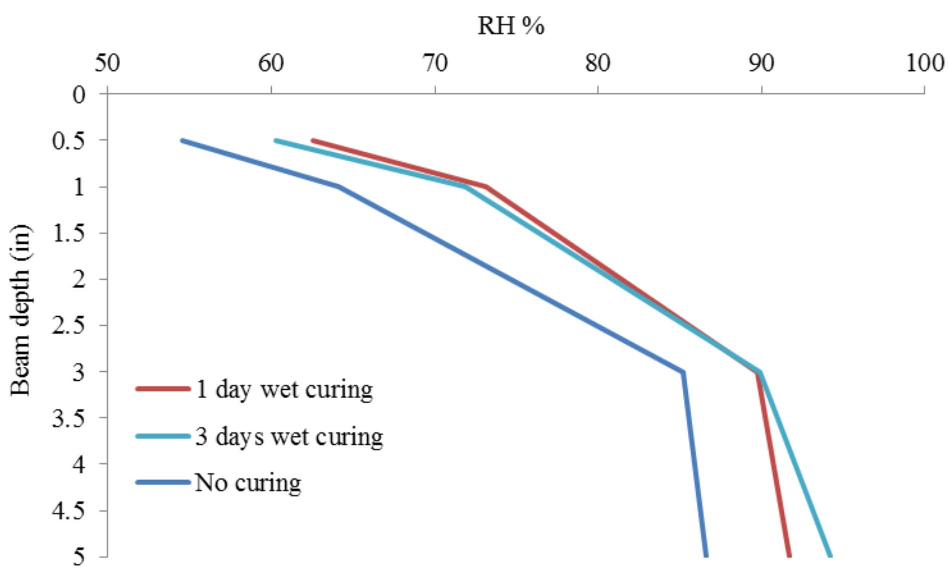

Figure 2 - 21: The RH profiles after 50 days for different methods for concrete beams

Figure 2 - 22 shows the integrated area under the RH profiles over the age for the wet curing and no curing methods. This graph is an indication of the total moisture loss for the sample.

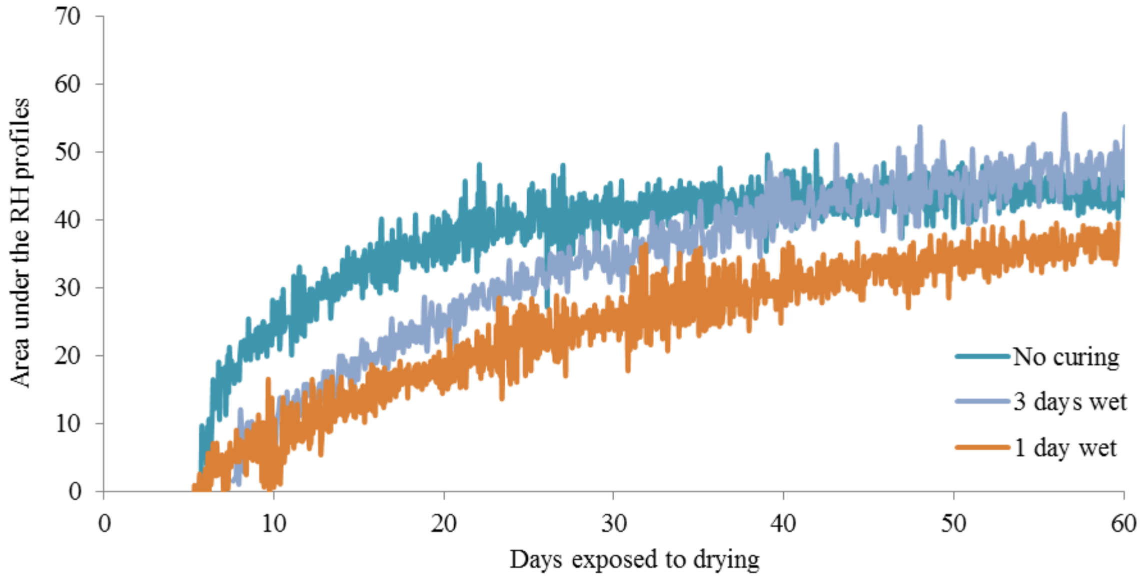

Figure 2 - 22: Integrated area under the RH profiles (depth x RH) over the age for concrete beams

2.4 DISCUSSON

2.4.1 Paste Beams

Figure 2 - 6 shows how the deformation for a paste beam increases and then starts decreasing after three days. Figure 2 - 7 shows that the weight of the beam decreases quickly and then starts to level off over time. This data is included to show the results for a typical specimen.

The maximum deflection from this method was always found to be at the middle of the beam. This is to be expected since the beam was not restrained and is assumed to lose water uniformly over its surface. This means that the moisture gradient between the top and the sealed bottom of the beam should be consistent over the beam. The paste beam starts to deflect downwards because the moisture gradient in the beam decreases. This water loss would be expected until the internal RH of the beam reaches equilibrium with the ambient.

Figure 2 - 8 shows that the specimens that did not receive curing lost moisture faster than the specimens that had received some amount of wet curing. This result suggests that there is a decreased porosity in the specimens that received the extended curing. In Figure 2 - 9 it can be seen that the wet curing lead to a greater degree of maximum deflection after a certain age. It can also be seen that this point of maximum curling occurred after a later number of drying days with prolonged curing times. Again this data suggests that the prolonged wet curing refined the pore structure of the paste. It is likely that when the moisture is lost in the small capillaries that this will cause a greater amount of shrinkage in the cement paste. This statement is supported by equation 2 - 3. As the radius of the pore decreases the pressure produced should increase by an inverse relationship.

Others have noticed similar observations. Hedenblad (1997) suggested that with prolonged wet curing that the top surface will have fine capillary pores due to the longer hydration process. Moreover, additional curing may increase the water content of the thin paste bars, which will increase the drying time. Findings are in conflict to work by Supernant (2002) who claims that curing primarily impacts when concrete will start to curl and not the magnitude of curling. Others have also suggested that extended curing only delays curling; it does not reduce curling (ACI 360R-2006).

The results in Figure 2 - 10 show that when the beam is cured by sealing it in a plastic sheet that the beam lost moisture more slowly than wet curing. Figure 2 - 11 shows that the maximum deflection was very similar between the wet curing and the sealed specimens for the same duration of curing. Again, it was witnessed that the longer the material was cured, the more curling occurred.

Specimens that are cured by not supplying extra water but sealing them seem to have a similar performance as the wet curing techniques. They seem to promote hydration and the production of small pore size distribution. One difference between the specimens is that the sealed cure seems to lose less moisture than the wet cured samples. This suggests that additional water is added to the wet cured samples during the curing process. However, this additional water does not seem to largely impact the amount of curling that occurs. This observation is in line with the current mechanisms for drying shrinkage that suggest water loss at the walls of a capillary are the primary cause of drying shrinkage. By adding more bulk water to the paste then this does not impact the water at the capillary walls.

Figure 2 - 12 shows that the additional wet curing seems to increase the maximum curling of the paste for curing up until 14 days and then ultimately decrease the curling for longer curing. This can be seen that the curling for mixtures with a 0.50 w/c start to decrease after 28 days of wet curing and after 14 days for 0.34 w/c. A specimen was not investigated for a 0.42 w/c but this would be expected to be between these values. The reason for this behavior is not clear. Other researchers have reported similar observations in concrete. Work by Perenchio relating the period of moist curing and drying shrinkage for concrete with various w/c, showed that periods of curing greater than 4 to 8 days and less than 35 to 50 days may increase the drying shrinkage (ACI 209.1R-2005).

Considering the specimens with no additional curing in Figure 2 - 12, the maximum deflection of the sample with 0.42 w/c has a similar performance to 0.34 w/c for a low amount of curing and then increases to be very similar to a 0.50 w/c after 7 days of curing.

Past researchers have shown that as the w/c increases so does the drying shrinkage (U.S. Bureau of Reclamation 1975; Schmitt and Darwin 1999; Darwin et al. 2004). In general, samples of higher w/c ratios have more construction water and, due to less fine pores at the surface, they start drying earlier, which will increase the drying rate (Hardenblad 1997). It is not clear why the 0.42 w/c specimen showed similar performance to the 0.50 w/c after 7 days of curing.

Figure 2 - 13 and 14 summarize the weight loss of the specimens for different w/c ratios at the maximum curling deflections (before curling down) and at 11 days. Both graphs show less moisture loss with an extended curing period. The reason, as explained earlier for Figure 2 - 12, is due to the finer pores at the surface of the sample after the wet curing which delay the external drying and reduce the drying rate (Hedenblad 1997).

2.4.2 Concrete Beams

The surface strain and tip deflection results after about 40 days in Figures 2 – 15 and 16 show that there does not seem to be much difference in performance with no curing and with 1 and 3 days of wet curing. The wet curing for 3 days is not beneficial for this model and at the boundary condition explained earlier. After about 20 days, the curling deflection of the mentioned specimen is higher than that of the 1 day wet curing method, and it demonstrates the maximum deflection amongst all techniques after 40 days. There is a high degree of uncertainty in predicting shrinkage of concrete structures, however, because this property varies considerably with many parameters, including concrete composition, source of aggregate, ambient relative humidity, specimen geometry, and the ratio of the exposed surface to the volume of the structural element. Since the moisture movement through the material causes drying shrinkage, this problem highly depends on the size and shape of the specimen, and it is hard to expect to reach a final value due to the long drying duration in normal size samples (RILEM TC 107 1995; Al-Manaseer, Espion, and

Ulm 1999; Bazant 1999) but not difficult for the sufficiently thin paste specimens (Wittman et al. 1987).

Moreover, the slow development of shrinkage over time makes it difficult to obtain an accurate prediction for a given concrete from short-term laboratory measurements (ACI 224R-2001). Lyse (1935), Carlson (1938), Keene (1961), and California Department of Transportation (1963) reported that the duration of moist curing of concrete does not have much effect on ultimate drying shrinkage; as far as the cracking tendency of the concrete is concerned, prolonged moist curing may not be beneficial. More work is needed to look at curing periods longer than 3 days in the concrete testing.

Besides what was interpreted in the previous section about paste beams' results, it is noticeable to consider the capillary tension as well. The shrinkage of the concrete is caused by the shrinkage of the paste (Pickett 1956) as shown in Equation 2 - 1; therefore it is expectable to get the same result in the same boundary condition as before. The more fine pores there are, the more capillary tension would be gained, as expressed in Equation 2 - 2 and 2 - 3 (Mackenzie 1950; Adamson and Gast 1997; Bentz et al.1998).

Figure 2 - 17 shows that the relative humidity of the top surface at 0.5" from the exposed side changes faster than the bottom of the beam at depth=5". This is expected as the surface of the beam is exposed to a much greater degree of drying.

The RH at top layers which are closer to the exposed surface tends to be equilibrated with the ambient RH by losing water through the capillary pores. This equilibrium will reach to the bottom layers at later ages since it takes longer for the internal moisture to be transported to the external exposed surface (Monfore 1963).

Figures 2 - 18, 19, and 20 show the RH profiles for no curing, 1-day, and 3-day wet curing. They present that the no curing has a faster decrease in relative humidity over the depth after exposure, while the 1-day and 3-day wet curing methods have slower moisture loss over the age. Figure 2 - 21 compares the RH profiles of the abovementioned methods after 50 days; the no-curing methods has less humidity at and near the top surface while the RH values near the bottom layers are very close together for no-curing and wet curing methods.

Figure 2 - 22 shows the integrated area under the RH profiles for the aforementioned methods. The graph for no-curing technique is above those for the wet curing techniques at the early ages, but they meet each other at later ages.

These graphs for no curing technique validate the reason for having the faster weight losses due to the higher porosity concrete. The graphs for wet curing techniques keep increasing, showing their continuous water losses, their slower drying rates, and their delay in reaching the maximum curling deflections which could be expected in later ages, as seen in Figure 2 - 15.

2.5 CONCLUSIONS

In this chapter wet curing methods were compared to sealed and no-curing methods; it was found that wet curing on the exposed surface of a sealed beam decreases the rate of weight loss from drying but increases ultimate curling deflection. This data suggests that extended wet curing would be expected to cause an increase in the amount of curling that occurs in a slab on grade. Similar observations have been observed for drying shrinkage in concrete beams but never applied to increases in curling. Due to the wet curing process, the surface of the beam has a finer pore-structure (Hedenblad 1997) and consequently a higher negative pressure or capillary tension upon drying (Mackenzie 1950; Adamson and Gast 1997; Bentz et al.1998). This increase in capillary tension has been suggested to be the primary mechanism for drying shrinkage (Lane, Scott, and Weyers 1997).

In all of the tests presented a one dimensional drying front was used through use of impermeable boundaries. Nicholson (1981) showed that serious shrinkage curling due to an increase in moisture gradient can occur when concrete slabs are cast on an impervious base. Because curling and drying shrinkage are both a function of potentially free water in the concrete at the time of concrete set, curing methods that retain water in the concrete will delay shrinkage and curling of enclosed slabs-on-ground. If the drying front occurs from the top and bottom of the concrete then the curling would be reduced because of the decrease in the gradient.

CHAPTER III

IMPACT ON CURING COMPOUNDS TO REDUCE CURLING IN CONCRETE FROM DRYING SHRINKAGE

3.1 INTRODUCTION

This chapter reviews the effectiveness of curing compounds to resist the curling from differential drying by comparing one of the common curing techniques to wet curing method.

Liquid membrane-forming compounds consist of waxes, resins, chlorinated rubber, and other materials that reduce evaporation of moisture from concrete. They are the most widely used method for curing not only freshly placed concrete, but also for extending the curing of concrete after the removal of forms or after early wet curing (Kosmatka et al 2003).

According to ACI 308R-01 curing compounds have several advantages:

1. *They do not need to be kept wet to ensure that they do not absorb moisture from the concrete;*
2. *They are easier to handle than burlap, sand, straw or hay; and*
3. *They can often be applied earlier than water-curing methods (immediately after finishing without the need to wait for final setting of the concrete).*

Usage of curing compound followed by water-saturated coverings is more common in bridge construction (Krauss and Rogalla 1996). Liquid membrane-forming compounds for curing concrete meet the requirements of ASTM C 309 include:

- Type 1, clear;
- Type 1D, clear with fugitive dye;
- Type 2, white pigmented;
- Class A, unrestricted compositions or wax-based products; and
- Class B, resin-based compositions

Loss of some moisture from the surface of concrete cured with these compounds is allowable; depending on the application and ambient conditions in the field, these compounds have a variable potential for water retention (Mather 1987, 1990; Shariat and Pant 1984; Senbetta 1988). The amount and type of curing can affect the rate and ultimate amount of drying shrinkage. Curing compounds, sealers, and coatings can trap free moisture in the concrete for long periods of time, resulting in delayed shrinkage (Kosmatka et al 2003).

The curing compounds should be agitated or stirred before use and applied uniformly at the recommended rate. Since a textured surface has at least twice the area of a floated surface and verification of coverage rate is more difficult for deeply textured surfaces, it has been recommended that curing compounds should be applied in two applications to ensure uniform and more complete coverage (Shariat and Pant 1984). They can be applied by hand or power sprayer with proper nozzles in the pressure range 25 to 100 psi. Also, they should be applied immediately after the final finishing of the concrete, after the surface water disappears, since a delay could cause the concrete surface to dry and the compound might absorb into the concrete, which would deter the formation of the desired membrane (ACI 308R-01). On the other hand, applying the curing compound on freshly cast concrete might result in map cracking; the disappearance of surface water will be stopped temporarily, but bleeding might continue. The bleed water will reduce the capability of the compound to maintain the moisture content of the concrete. White-pigmented compounds help guarantee uniform coverage and are considered to reflect light and heat for floors exposed to sunlight. A typical application of a curing compound is shown in Figure 3 - 1.

Figure 3 - 1: The power-driven spray to perform a uniform application on a tinned surface (Ye et al, TxDOT 2009)

The application rate of the curing compound should be determined based on surface texture and application device in order to obtain uniform coverage. The five factors listed below affect the curing compound application (Minnesota DOT 1999; Texas DOT 2009; Iowa DOT 2002):

- nozzle type: spray pattern, droplet size, pump pressure, spray angle, flow rate
- nozzle spacing and boom height: adjusting for 30 percent overlap of spray pattern edge
- nozzle orientation

- cart speed
- windshield

It was concluded that non-uniform coverage is mainly caused by damage to the nozzle or orifice. Complete coverage of the surface must be attained because even small pinholes in the membrane will increase the evaporation of moisture from the concrete. Curing compounds should be uniform and easy to maintain in a thoroughly mixed solution (Kosmatka et al 2003).

It is the goal of this research project to examine the performance of different curing compounds on the ability to reduce curling in concrete and paste specimens from differential drying. The results from different brands of curing compounds, application rates, and single and double coatings are investigated.

3.2 EXPERIMENTAL INVESTIGATIONS

3.2.1 Paste beams

3.2.1.1 Materials

The Portland cement used in these tests was a type I/II according to ASTM C 150, and its oxide analysis per ASTM C 114 and the phases' concentrations are shown in the following Table 3 - 1. The paste mixutures in this experiment had a water to cement ratio (w/cm) of 0.42.

Table 3 - 1: Oxide analysis of the cement used for paste beams and the phase concentrations

Chemical Test Results	
SiO_2	20.23
Al_2O_3	4.77
Fe_2O_3	3.23
CaO	64.15
Phase concentrations	
C_3S	70.69
C_2S	4.68
C_3A	7.18
C_4AF	9.83

Three different curing compounds were used in this project; these products were chosen as they were from different chemical families and were used by three different states. The standardized specifications are summarized in Table 3 - 2 according to the MSDS for the product. The first curing compound (C1) is high solids, white-pigmented, and Poly-alphamethylstyrene-resin-based and it dries in approximately one hour. The second curing compound (C2) is a water-based, white-pigmented curing compound series; it has resin-based dispersions with selected white pigments and typically dries in 1-2 hours. The third one (C3) is of a water-based, white-pigmented concrete curing compound series, with a wax-based dispersions and selected white pigments and typically dries in two hours.

Table 3 - 2: Curing compounds' specifications

Curing compounds	Type (Per ASTM C 309)	Drying time	Basis
C1	Type 2, Class B	1 hour	Poly-Alphamethylstyrene
C2	Type 2, Class B	1-2 hours	Water-Based, Resin-Based
C3	Type 2, Class A	2 hours	Water-Based, Wax-Based

3.2.1.2 Sample preperation and methods

The paste mixtures were prepared according to ASTM C305. Three paste beams with dimensions of 39.4” x 2.4” x 0.5” were prepared in plastic molds from each mixture. For this testing, all specimens were stored in an environmental chamber at 73˚ F and 40% relative humidity. All specimens were cured using wet burlap for 5 hours before being covered in curing compound. Before and after the application of the curing compound, the samples were weighed and finally stored in the chamber room until 24 hours after mixing. Next the samples were demolded, weighed, sealed with wax, reweighed and stored on their sides in the chamber room. These samples were all sealed with wax on all sides except the top, on which the curing compounds are sprayed. Figure 3 - 2 shows the specimens covered with different curing compounds inside the chamber room. This test was adopted from previous work done by Burke (2004) to investigate the effectiveness of shrinkage reducing admixtures.

Figure 3 - 2: The specimens covered with curing compounds stored in the chamber room

3.2.1.3 Test procedure and measurement

For this testing the three different types of curing compounds were applied 5 hours after casting, which was the time required for the bleed water to disappear from the surface of the specimen.

Each curing compound was applied in three different volumes. A coverage that was about equal to the manufacturer's recommended dosage was used, as well as ones that were about 50% lower (low dosage) and 150% higher (high dosage), were used to evaluate the performance of different curing compounds and coverages. The curing compound was applied in a single layer with a Chapin 5797 flat nozzle for all products with a pump pressure of 40 psi, as suggested by the manufacturer. To modify the application of the compounds, three different nozzle distances were used with the same cart velocity as suggested by Vandenbossche (1999). For this purpose, a cart was constructed that runs on tracks and holds the nozzle at a controlled height. The cart was moved along the sample at a constant velocity. This constant velocity was obtained by using a metronome and marks with a known distance on the track. The cart was moved so that it crossed a mark at the exact same time the metronome sounded. Because the metronome supplied a beat at a constant interval, and the cart operator was able to move between the marked locations at a constant rate then this allowed the cart to move at an almost constant velocity. This velocity could be easily changed by changing the beat rate of the metronome. For all testing the velocity was kept constant and the coverage rate was adjusted by changing the height of the spray nozzle.

The coverage rate on samples cured by the curing compound was determined by the following Equation 3 - 1 (Vandenbossche 1999):

Equation 3 - 1: $$v = \frac{Coeff. \times F}{C \times w}$$

Where:

v = Cart speed, kilometers per hour (miles per hour)

Coeff. = 6 when using SI units (0.13636 with Imperial)

F = Flow rate, liters per minute per nozzle (gallons per minute per nozzle)

C =Desired coverage, liters per square meter (gallons per square foot)

w = Nozzle spacing, cm (inches)

The following picture in Figure 3 - 3 shows the schematic view of the spray coverage calculated by Equation 3 - 1. This equation is commonly suggested by the curing compound manufacturers to determine the correct coverage rate for an experiment.

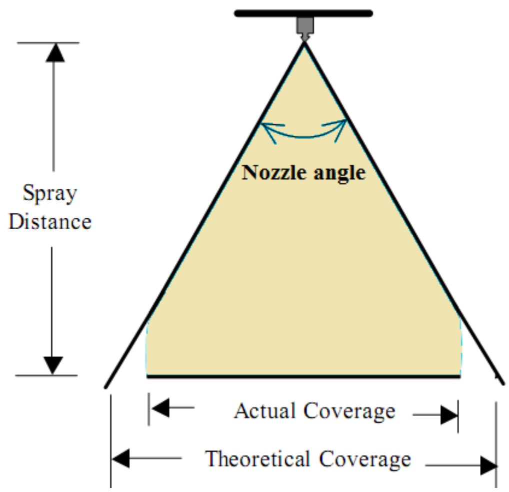

Figure 3 - 3: Schematic view of the spray coverage

The flow rate, cart speed, desired coverage, and spray distance used in this study to spray the curing compounds were computed by the equation. The velocity applied for all dosages was 1.33 ft./sec and the coverage time was 2.5 seconds; thus, the spray distances were 20.85”, 10.40”, and 6.95” for low, medium, and high dosages respectively.

To check the uniformity of the coverage and accuracy of the equation, some practice tests were done by using steel plates of known areas that were placed at a known height. These plates were weighed before and after applying curing compounds. By using the area of the plate and the weight of the curing compound the coverage could be calculated. A summary of the amount of applied curing compound and the standard deviation for each test is shown in Table 3 - 3.

Table 3 - 3: The curing compound coverage and standard deviation

Curing method	Basis	(gal/ft^2)	low	medium	high
C1, Single layer	Poly-Alphamethylstyrene	Coverage	0.0019	0.0040	0.0051
		STD	0.0002	0.0001	0.0000
C2, Single layer	Water-Based, Resin-Based	Coverage	0.0020	0.0037	0.0051
		STD	0.0001	0.0004	0.0002
C3, Single layer	Water-Based, Wax-Based	Coverage	0.0036	0.0048	0.0074
		STD	0.0001	0.0001	0.0003
C3, Double layer	Water-Based, Wax-Based	Coverage	0.0027	0.0041	0.0056
		STD	0.0001	0.0001	0.0003
1-day wet + C3 Single	Water-Based, Wax-Based	Coverage	-	0.0038	-
		STD	-	0.0002	-

A double layer of C3 was tested as well. This application was achieved by applying two layers whose sum would equal the required value. Also, the combination of 1 day wet curing and a medium application rate of C3 was tested.

The measurement of the beam's deflection over time and its weight's measurement were also explained previously in chapter 2; two ends of the specimen are attached to a flat aluminum plate with the uncoated surface facing the plate to measure the curling deflection with a caliper that is accurate to 0.0005". The weight of the sample is also measured with time using a scale that is accurate to 0.1 grams.

3.2.2 Concrete beams

3.2.2.1 Materials

The cement, aggregate, fly ash, and moisture barrier used in this experiment were the same as in the previous chapter for concrete beams; samples include cement type I according to ASTM C 150 and Oklahoma aggregates as well as a Class C ASTM C 618 fly ash. To seal the concrete beam samples, a synthetic moisture barrier was used as a form liner. The interface between the beam and the water membrane was sealed with hot glue to insure a good bond was maintained throughout the test. The cement chemical analysis per ASTM C 114 and the phases' concentrations are shown in the following Table 3 - 4.

Table 3 - 4: Chemical analysis of the cement used for concrete beams and the phases' concentrations

Chemical Test Results	
SiO_2	21.13
Al_2O_3	4.71
Fe_2O_3	2.55
CaO	62.06
Phase concentrations	
C_3S	52.14
C_2S	20.22
C_3A	7.69
C_4AF	7.96

3.2.2.2 Mixture Proportions and Methods

The mixture proportion and the mixture procedure were explained in chapter 2. However, this concrete was not air entrained. The water to cement ratio used in this experiment was equal to 0.41 for concrete beams. All of the aggregate, both coarse and fine, were charged into the mixer along with approximately two-thirds of the mixing water. The combination was mixed for three minutes. Next any clumped fine aggregate was removed from the walls of the mixer. Then the cement was loaded into the mixer, followed by the remaining mixing water. The mixer was turned on for an additional three minutes. Once this mixing period was complete, the mixture was left to "rest" for the following two minutes while the buildup of material along the walls of the mixer was removed. Next the mixer was started and the admixtures were added and the mixer was allowed to run for the remainder of the three minutes (ASTM C 192). The slump (ASTM C 143), unit weight (ASTM C 138) and the air content (ASTM C 231) were measured.

3.2.2.3 Sample preperation, Casting and Curing

In this experiment the size of the concrete specimen investigated was 7.5′×6″×8″, with all sides sealed with a type of synthetic moisture barrier except the top surface for each specimen. These specimens were all stored on their side in an environmental chamber at 73˚ F temperature and 40% relative humidity. After placing and vibrating the concrete in 3 different layers, the top surface was made flat with a screed. Next a micro-surface was applied with a burlap drag, and then the surface was finally tined using a comb. The comb had transverse grooves 1/16″ wide, 1/4″ deep, and center to center spacing of 1″ between the tines based on ODOT Standard Specification for Highway Construction. For this testing only curing compounds C3 and C1 were investigated. A single layer of C3, single layer of C1, and a double layer of C3 were investigated in this experiment. The layers were applied in two equal coatings so that their sum equaled the total desired coverage. The beams were flipped on their sides and placed on wooden dowels either after 24 hours or after the curing methods were completed. This was done to minimize the influence of gravity on the results. After placing the beam on its side, it was fixed at the end with a C-clamp, steel plates, and rubber bearing pads.

3.2.2.4 Test Procedure and Measurement

The RH was measured 5 days after casting. DS1923 Hygrochron Temperature/Humidity Logger iButton sensors were used to measure RH at 4 different distances: 0.5″, 1″, 3″, and 5″ from the finished surface.

The curling height of the beam was measured at two different locations: 45″, and 89.5″ from the end of the beam. The deflection gauges were fixed using magnets on the steel support beneath the concrete beam. The accuracy of this gage was 0.0005”. Also, the surface strain of the beam was measured after flipping the beam. Curing compound was sprayed on the samples about 2 hours after casting with a similar method as with the paste beams. In order to obtain the desired coverage, many repetitions were completed and checked with steel plates. This allowed for very precise nozzle height and speed to be found that corresponded to a known amount of coverage. The amount of compound used for these experiments was chosen as 5.0 m^2/L (200 ft^2/gal) based on the ASTM C 309; therefore, “C3, D, medium” was performed in two different layers each with 100 ft^2/gal coverage.

3.3 EXPERIMENTAL RESULTS

3.3.1 Paste Beams

Figure 3 - 4 and Figure 3 - 5 show weight losses and deflection over time, respectively, for different application rates of curing compound C2. Label “C2, S, low” means a single layer of C2 in medium rate and so on. These values are shown as they are typical results for one of these tests.

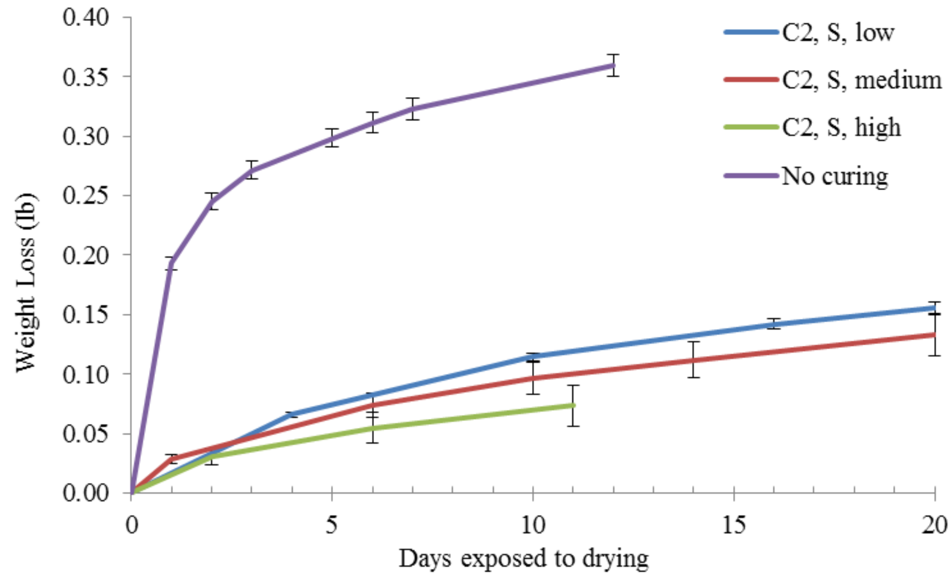

Figure 3 - 4: Moisture loss for a paste beam over time for C2 in single layer compared to no curing method

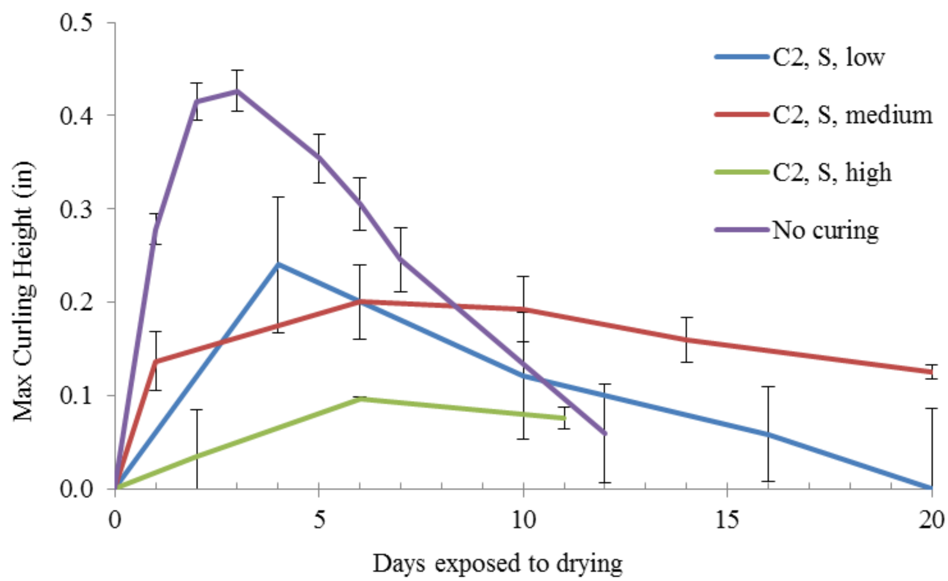

Figure 3 - 5: The maximum curling height vs. age for C2 in single layer compared to no curing method

Figure 3 - 6 summarizes the deflection results for all curing compounds and shows the maximum deflection that the specimen experienced versus the application rate of different curing compounds. Also included in the graph is a line showing the deflection for a specimen with no curing compound, one day of wet curing, and a specimen that was cured for 1 day and covered

with a single layer of curing compound C3. Also, the graph includes the maximum curling height for 1 day of wet curing to be compared and discussed later.

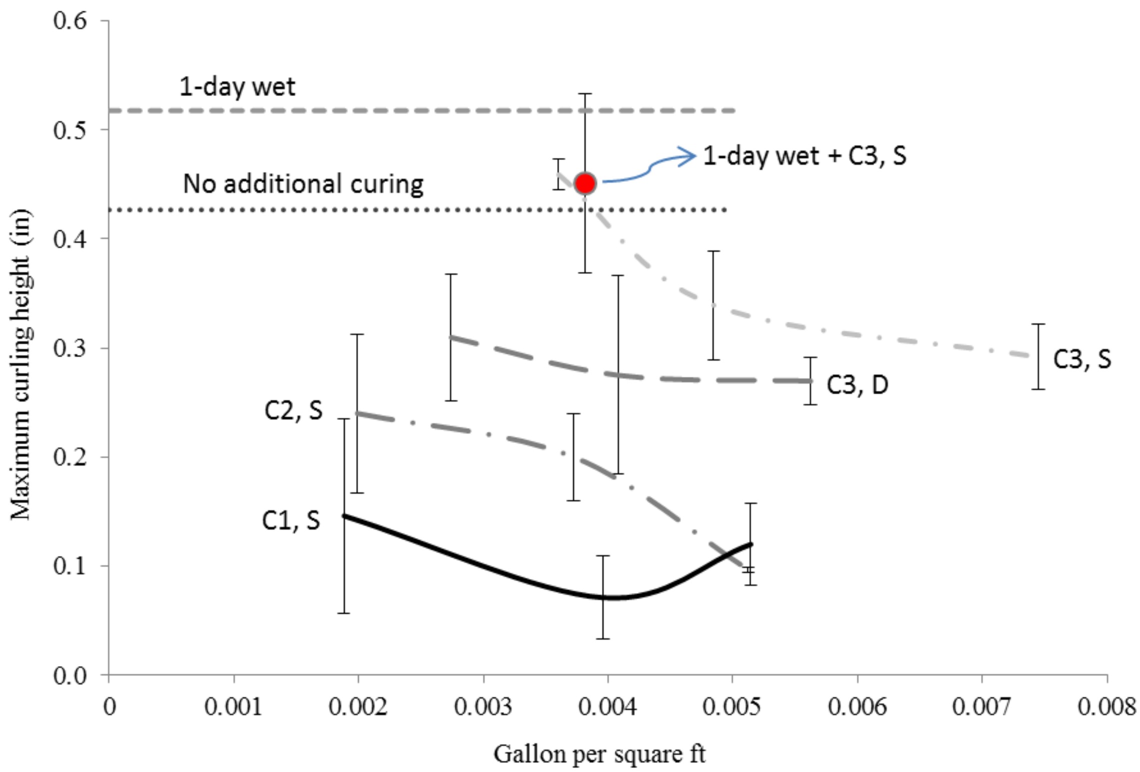

Figure 3 - 6: comparison between highest deflections versus different coverage of curing compounds on paste beams

Figure 3 - 7 shows the weight loss versus the coverage after 11 days for the different applications of curing compounds. The graph is shown at 11 days because this provided a good amount of time for drying and this measurement existed for all of the data.

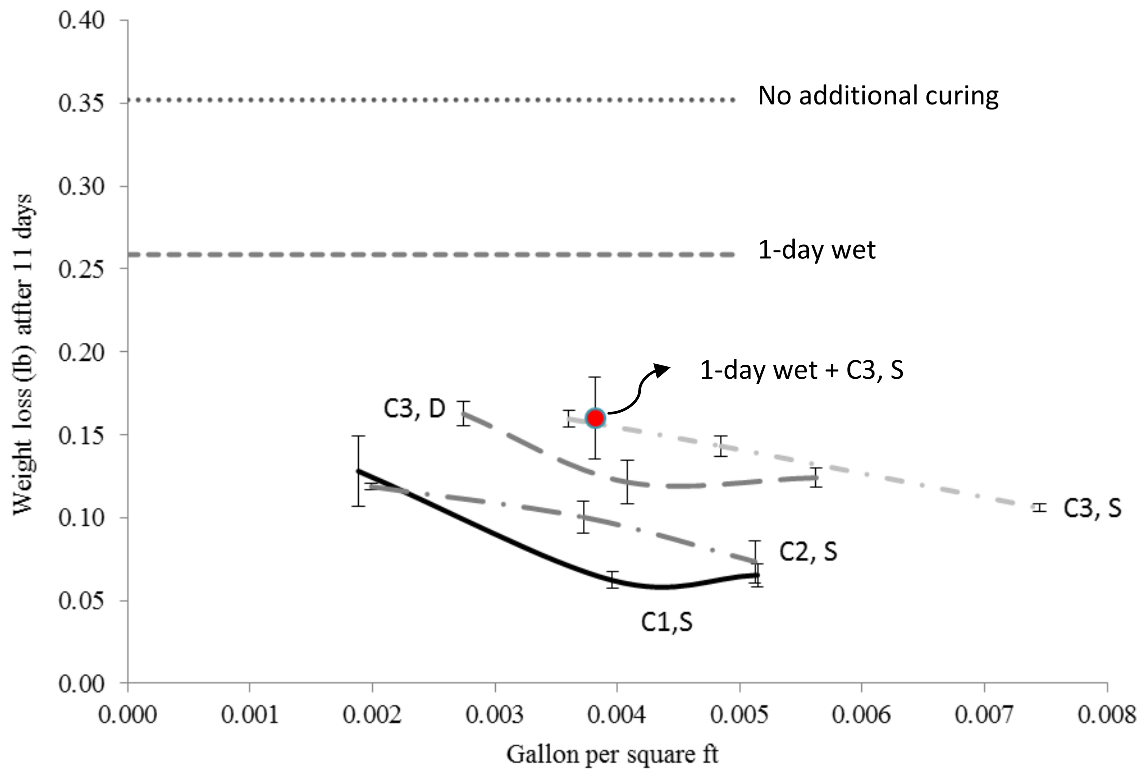

Figure 3 - 7: comparison between weight losses versus different coverage of curing compounds on paste beams after 11 days

Figure 3 - 8 and Figure 3 - 9 show the maximum curling deflection and the weight loss after 11 days versus additional curing time for the wet cured specimens in comparison with specimens cured with curing compounds; w/c ratio for all specimens is 0.42. A number of curing compound techniques of interest have been included including a single layer of C3 with a medium application. Also, graphs include the combination of 1-day wet curing with a single layer of C3 in medium application rate to be compared later.

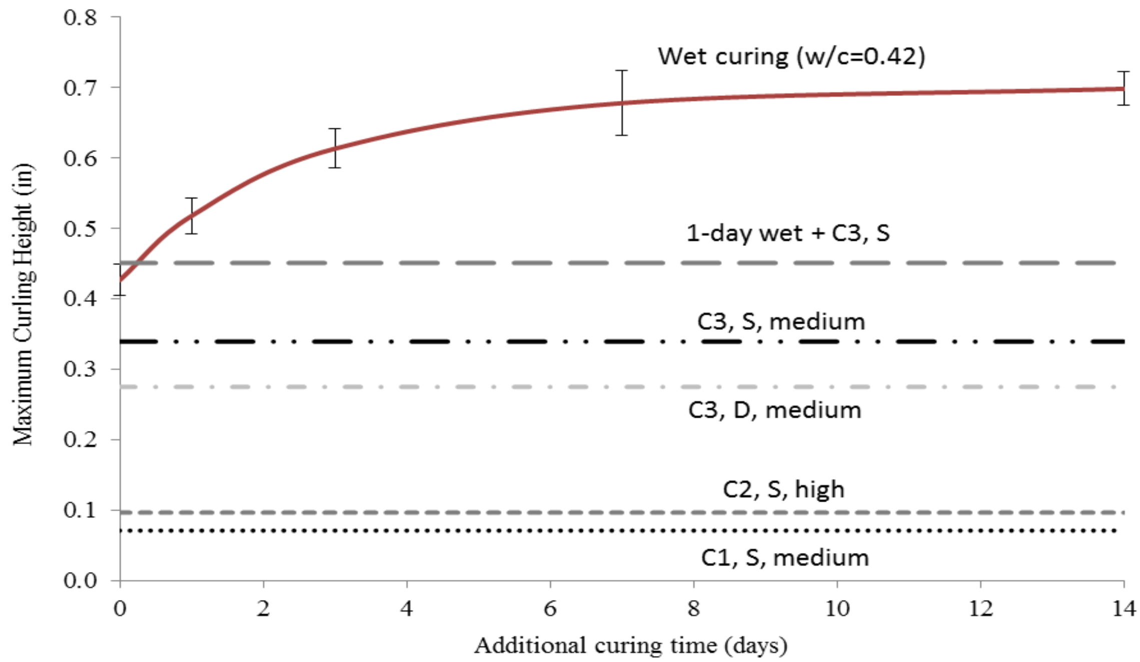

Figure 3 - 8: The maximum deflections of wet cured paste beams versus additional curing time compared to curing compound methods

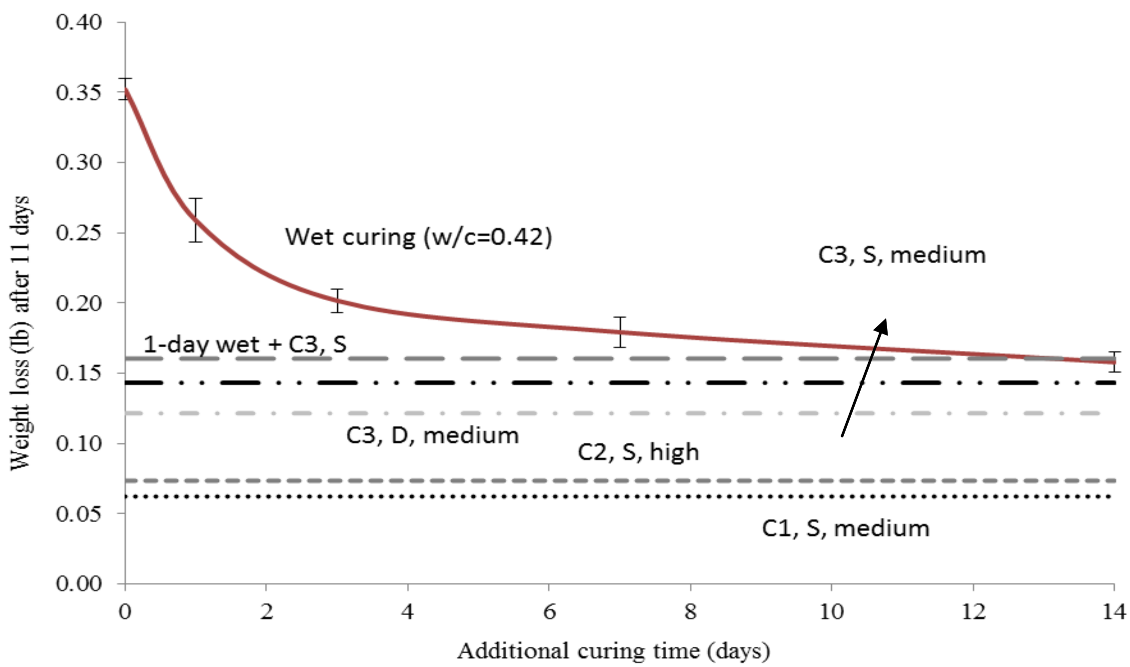

Figure 3 - 9: The weight losses of wet cured paste beams after 11 days versus additional curing time compared to curing compound methods

3.3.2 Concrete Beams

Figure 3 - 10 shows the surface strain of the concrete beams with different curing compounds compared to those with no curing.

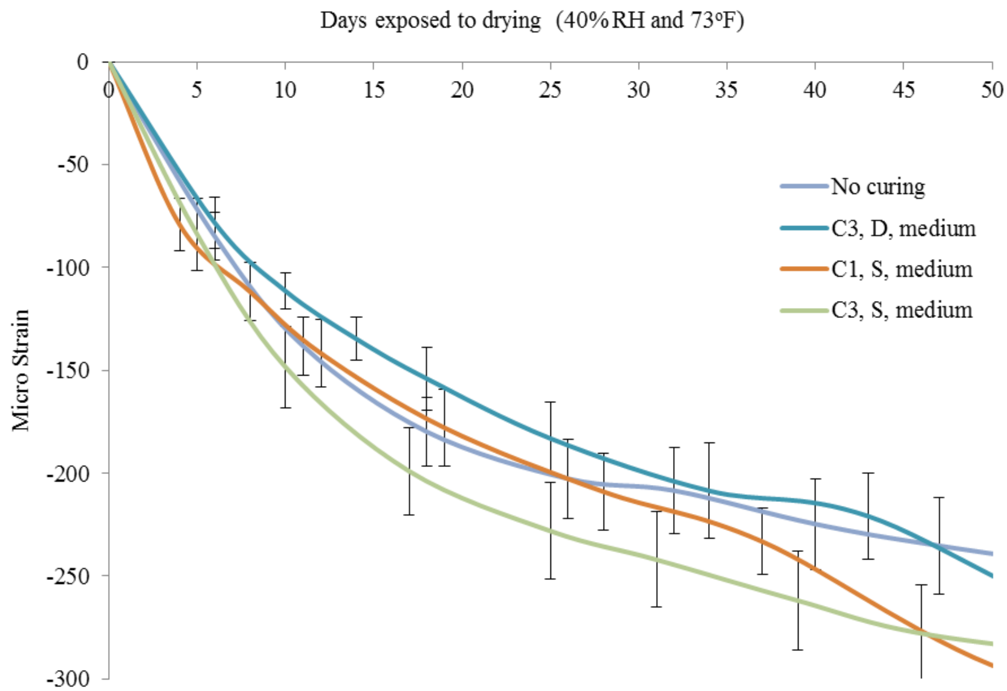

Figure 3 - 10: Surface strain of the concrete beams with curing compounds over the time

Figure 3 - 11 and Figure 3 - 12 show the typical graphs for the relative humidity of the beam during the exposure and RH profiles at different depths of the beam with a double layer of C3.

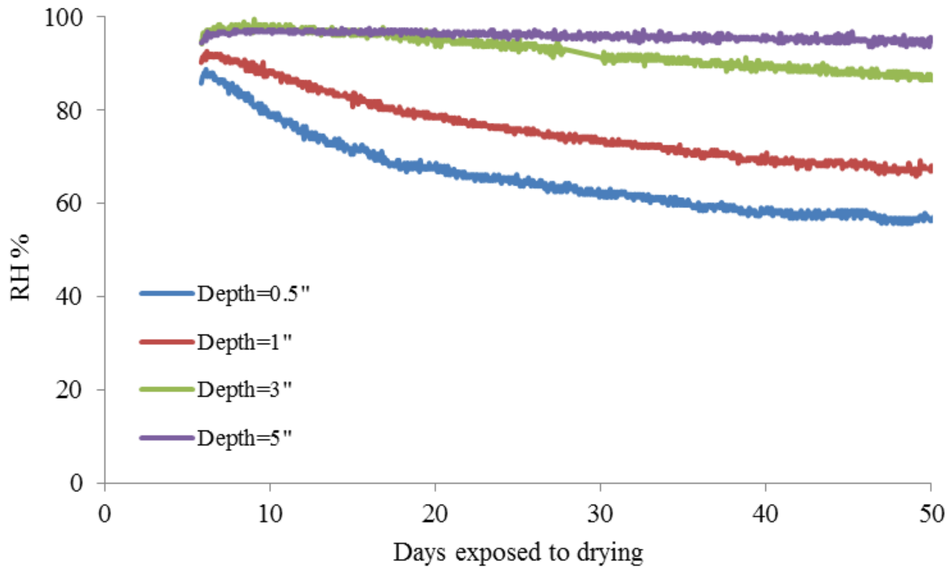

Figure 3 - 11: Relative humidity at different depths of concrete beam C3-D during the age

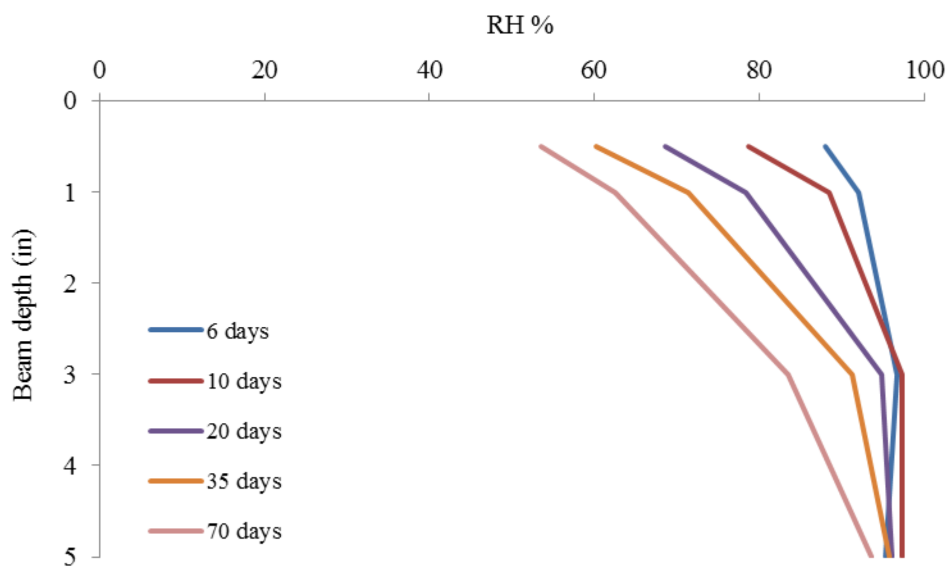

Figure 3 - 12: RH profiles for 6, 10, 20, 35, and 70 days after exposure for concrete beam C3-D

Figure 3 - 13 shows the area under the relative humidity profiles for the abovementioned beams over the age after exposure; however RH measurement was started 5 days after casting due to the problem mentioned earlier in previous chapter.

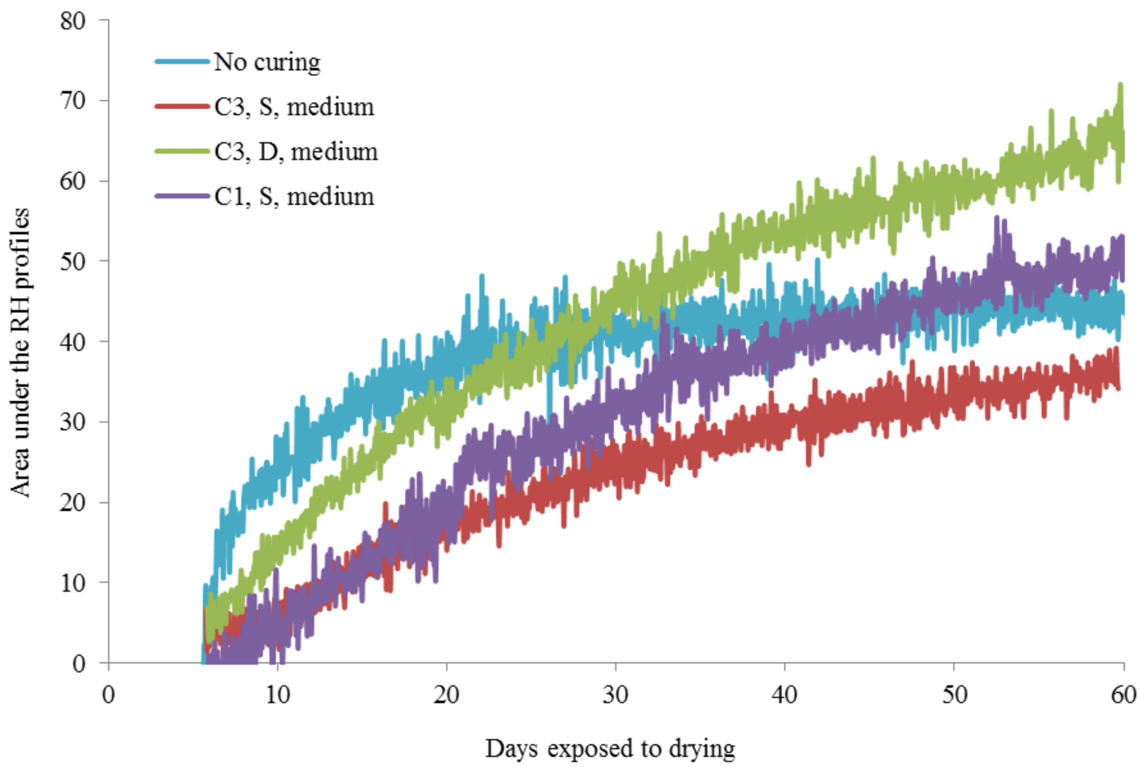

Figure 3 - 13: Integrated area under the RH profiles over the time for concrete beams

3.4 DISCUSSION

3.4.1 Paste Beams

Figure 3 - 4 shows that the curing compound C2 has reduced the water loss when compared to the specimen with no curing. As the application increased the curling decreased. Figure 3 - 5 shows curling height is less with a higher dosage of curing compound compared to no curing. The curing compound retains the moisture content for a longer age by making a thin membrane, but it does not terminate the loss of moisture completely.

In Figure 3 - 6 it can be seen that, typically, as the amount of curing compound applied increased, the maximum curling height of the specimen decreases. The C3 curing compound in a single layer reduces curling with higher application rates; however, the low application rate of C3 in a single layer had a very similar amount of curling as the sample with no curing compound. The deflection from the samples with 1 day of additional wet curing plus a single layer of C3 also had a similar performance as the sample with no curing. There is a slight improvement over the sample with 1 day of wet curing. The double layer of C3 shows a slight reduction in curling from the increase in the curing compound application. Of the samples investigated, it was surprising that there was not much improvement in performance with an increase in the application of the curing compound. The increase in application of C2 also decreased the maximum deflection. Finally, the increase in application rate of C1 also did not show much of a difference. It was observed that the effectiveness of a curing compound has some limiting value in three of the different experiments. This may be because a certain curing compound has a limit of effectiveness. If more curing compound is applied than this limit value, then there is not much benefit in the performance. Furthermore, it appears that a double layer of curing compound reaches this limit at a much lower amount of curing compound application than a single layer of curing compound. This probably is associated with the increased effectiveness in coverage for a double application of curing compound.

Figure 3 - 7 shows that all of the specimens after 11 days of drying that used curing compounds had a lower loss of moisture then those that did not.

The moisture retention capability of the single layer of curing compound was the highest with C1 and the lowest with C3. The double layer of C3 did show an improvement in performance over the single layer. This data suggests that a curing compound does a much better job of keeping the water inside of the paste specimen than other methods. Also it appears that some curing methods are more effective than others at keeping moisture in a sample.

Figure 3 - 8 shows that each of the curing compounds had the ability to reduce curling below levels of wet curing in the specimen. It can also be seen that the prolonged wet curing increased the curling of the specimen as discussed in chapter 2. Figure 3 - 9 shows that after 11 days of drying that all of the curing methods were able to keep the moisture loss less than the specimen that had the 14 days of wet curing or less. This ability to keep moisture in the specimen helps to minimize the curling from the differential shrinkage. Figure 3 - 9 also validates that the best curing compounds always have the least water loss and that even more additional wet curing only increases the water content and shrinkage possibility due to the finer pore structure compared to curing compounds.

The combination of 1-day wet curing plus "C3, S" in the previous graphs compared to 1-day wet curing method shows that rapid drying of the surfaces at the conclusion of the specified curing period should be avoided. The best curing environment is to keep the concrete continuously wet during the curing period. The curing and protection should not be discontinued suddenly (ACI 224R-2001).

3.4.2 Concrete Beams

Figure 3 - 10 shows the double layer of C3 has the least surface strain, while the single layer of the same curing compound in the same coverage has the most surface strain. C1 in a single layer has smaller strain than C3 in a single application in the same coverage. The no-curing method curls up very slowly after about 25 days while other beams continue curling up.

Some different trends were obtained in the concrete beam data than those in the paste beams. For example, sample C3, S was found to perform worse than the no curing. This was unexpected.

However, the error bars for the two samples do overlap one another, and so there is no statistical difference between the results.

Although it is difficult to tell, it may be that the specimen with the single layer of C3 was not applied uniformly over the tined surface of concrete beam. Although C1 had the best performance on the paste beams, this was not the case on the concrete beams. One observation that the double layer of C3 performs better than the single layer of C1 was unexpected. This could be attributed to the ability to provide a much more uniform coverage of the double layer of C1.

Figure 3 - 11 and Figure 3 - 12 show the typical graphs of relative humidity over the depths. The RH in deeper depths decreases more slightly, and RH profiles show the speed of the RH reduction is higher for the top of the beam than its bottom.

Figure 3 - 13 shows that a no-cured sample has a faster drying rate than other beams at the early age, while samples with curing compounds have a slower drying rate. After about 25 days the slope of the drying rate of the no curing technique becomes zero, while this slope is increasing for other samples covered with curing compounds.

In the previous chapter about the paste beams it was explained that the no-curing technique has a faster water loss rate; this is true about the concrete beams, as well. The porous surface of a non-cured beam loses the construction water faster until after about a month when the curling rate lessens. Other beams covered with curing compound continue curling up as long as this moisture loss rate increases, Figure 3 - 13.

3.5 CONCLUSIONS

Different curing compounds with different coverages were compared. The poly-alphamethylstyrene-resin-based curing compound (C1) had the best performance with a comparable coverage rate in the paste beam tests. The water and wax based curing compound (C3) curing compound performed the worst and the water and resin based curing compound (C2) was between these two. As the coverage of the curing compound increased so did the ability to limit moisture loss and therefore curling. A double layer of a curing compound was shown to provide improved performance over a single layer of curing compound.

Curing compounds appear to limit moisture loss to a greater degree than wet curing of up to at least 14 days or no curing methods. This reduction in moisture loss seems to correspond to a reduced amount of differential shrinkage and therefore curling in the specimens investigated.

In the concrete beams it was found that the double layer of the water and wax based curing compound performed better than the poly-alphamethylstyrene-resin-based curing compound. This is likely because it was applied in a double layer and therefore achieved a better coverage. This is especially important for applications with textured surfaces and with conditions that are not as favorable in the laboratory. Similar suggestions have been made by Shariat and Pant (1984). The uniformity of the application of the curing compounds is an important variable that needs to be controlled.

CHAPTER IV

CONCLUSION

In this project the effectiveness of different curing techniques in reducing the drying shrinkage effects and curling deflections of concrete and paste beams was considered; these methods, including no-additional-curing and wet curing for 1, 3, 7, 14, and 28 days of additional curing on paste beams, were compared to curing compounds in different application rates with single and double layers. Also, the concrete beams were tested under 1 and 3 days of additional wet curing in comparison with single and double layers of water and wax based curing compound and a single layer of poly-alphamethylstyrene-resin-based curing compound in a medium dosage. The results from both test specimens have similar results; the wet curing process on the specimens investigated did not reduce the drying shrinkage effects. In addition, the curing compounds were shown to reduce the curling and the weight loss of the specimens investigated when compared to ones with no curing or wet curing.

Wet curing on either a paste or concrete beam which is sealed from all sides except the exposed surface is not recommended if curling is a concern for that element such as a concrete pavement. Wet curing increases the moisture content of the beam during the additional curing process; therefore, the moisture loss lasts longer than usual, resulting in longer term moisture gradient. The exposed surface will have better properties under wet curing; i.e. less porosity and permeability compared to no-curing method; thus the drying rate is slower and it takes longer to reach equilibrium. Draining the pavement could reduce this one-sided moisture loss and consequently the moisture gradient, drying shrinkage, and finally the curling deflections.

The curing compound, however, had the best efficiency among all methods investigated in this project; the poly-alphamethylstyrene-resin had a very low water loss and beam deflection on paste specimens, while the water and wax based in a medium coverage with a double application was the best curing technique on concrete beams. The current research shows that the curing compound application in double layers has more benefit, since it is easier to provide a more uniform coverage than a single layer in the same dosage. The use of a double layer of curing compound is therefore recommended. Also, it was found that uniform application is highly important, regardless of the type of curing compound used.

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VITA

Amir Hajibabaee bana

Candidate for the Degree of

Master of Science

Thesis: REDUCING CURLING FROM DRYING SHRINKAGE OF CONCRETE PAVEMENTS THROUGH THE USE OF DIFFERENT CURING TECHNIQUES

Major Field: Civil Engineering

Biographical: Amir Hajibabaee bana was born in Karaj, Tehran, Iran on September 4, 1985.

Education:

- Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in December 2011

- Completed the requirements for the Bachelor of Engineering in Civil Engineering at University of Tehran, Tehran, Iran in June 2008.

Experience:

- Working on curing methods to reduce the drying shrinkage of the paste and concrete beams and, consequently, the curling of the concrete pavement as a Graduate Research Assistant in Civil Engineering Laboratory of Oklahoma State University, 2009-present.

- Working as a Supervisor in a project about retrofitting the severely corroded concrete piles of an old wharf in Shahid Bahonar Seaport, Persian Gulf, Iran, 2009.

- Investigating electrical resistivity of concrete in Construction Materials Laboratory of University of Tehran as my undergraduate research (internship), University of Tehran, 2006-2007.

- Testing concrete samples by chemical methods such as titration in Construction Materials Laboratory of University of Tehran to investigate steel corrosion in an old concrete structure in Kish Island, Persian Gulf, Iran and also in Bandar-E-Emam Port, Mah-shahr, Iran, 2005-2006.

Professional Memberships:

- Member of American Concrete Institute since 2009.
- Member of American Institute of Steel Construction since 2009

Name: Amir Hajibabaee bana Date of Degree: Dec, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: REDUCING CURLING FROM DRYING SHRINKAGE OF CONCRETE PAVEMENTS THROUGH THE USE OF DIFFERENT CURING TECHNIQUES

Pages in Study: 56 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study:

Reducing the deformation in concrete pavements through the use of curing at early ages was the main concern of this study. In this project, supported by the Oklahoma Department of Transportation (ODOT), results from the curling of the paste and concrete beams and the effects of curing techniques on them were discussed separately. Effectiveness of wet curing and how it changes the moisture gradient and surface properties, and also the efficiency of the curing compounds in reducing the moisture loss and curling deflections were investigated.

Findings and Conclusions:

The results showed that the wet curing process on the specimens investigated did not reduce the drying shrinkage effects. Wet curing on either a paste or concrete beam which is sealed from all sides except the exposed surface is not recommended if curling is a concern for that element such as a concrete pavement. Draining the pavement could reduce this one-sided moisture loss and consequently the moisture gradient, drying shrinkage, and finally the curling deflections.

The curing compound, however, had the best efficiency among all methods investigated in this project; the poly-alphamethylstyrene-resin had a very low water loss and beam deflection on paste specimens, while the water and wax based in a medium coverage with a double application was the best curing technique on concrete beams. The current research shows that the curing compound application in double layers has more benefit, since it is easier to provide a more uniform coverage than a single layer in the same dosage.

ADVISER’S APPROVAL: DR. TYLER LEY