

Examination of Drying and Psychrometric Properties of High Water-Cement Ratio  
Concretes

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# Examination of Drying and Psychrometric Properties of High Water-Cement Ratio Concretes

Thomas McNicol

## **Scholarly Abstract**

Moisture from concrete has been estimated to be responsible for over \$1 billion annually from damages in floor coverings. To prevent damages, flooring manufacturers require installers to test concrete moisture levels to determine if the concrete has dried sufficiently to receive flooring or covering. Two of the main tests used in the United States to determine concrete moisture levels are moisture vapor emissions rate (MVER) tests and relative humidity (RH) tests. Changes in ambient temperature can affect the results of both RH and MVER tests.

The goal of this study was to investigate the effects of ambient temperature changes on the RH of concrete, and compare the sensitivity of RH measurements to the results of MVER tests at the same ambient temperature. The RH of concrete was measured at 20%, 40%, 60%, and 80% of depth in each sample and tracked over a period of 24 days to develop drying curves at each depth, and drying profiles of each sample. The changes in concrete RH due to a change in ambient temperature were predicted using the psychrometric process and a model developed during this study. Due to size constraints on the concrete samples, ASTM 1869 had to be altered during the MVER tests.

Typical RH change in the concrete samples was under 4% RH after either an increase or decrease in an ambient temperature of 5.5°C (10°F). The psychrometric process predicted that the concrete RH would change between 20% - 40% RH after the ambient temperature changed by 5.5°C. Psychrometric properties were not able to full describe the behavior of air in concrete pores so a new model was created to better predict the change in concrete RH after a change in

ambient temperature. The developed model was able to predict concrete RH change within 5% error over the range of tested temperatures.

## General Abstract

Water is a key component of concrete and over the last decade concrete slabs-on-grade have increased in popularity in residential construction. Often flooring coverings, which are sensitive to moisture, are installed directly on top of the concrete. In some instances, the moisture levels in concrete are high enough to fail the floor covering, and the failures are responsible \$1 billion in damages annually. To combat this, flooring manufactures require moisture tests to be performed on the concrete; the two main tests are the moisture vapor emissions rate (MVER) and relative humidity (RH) tests. Manufacturers have also set acceptable moisture levels for installation for each test. Unfortunately, the results from the MVER and RH tests can vary based on the ambient air temperature, while the acceptable levels remain constant.

The goal of this study was to investigate the effects of ambient temperature changes on the RH of concrete, and compare the sensitivity of RH measurements to the results of MVER tests at the same ambient temperature. Concrete samples 6 in. in height were created, and RH sensors placed at different depths within the concrete to track the relative humidity of the concrete. The samples were left in two environmental chambers, one at 75°F and 50% RH and the other at 85°F and 50% RH, for 24 days during which the moisture levels were recorded. When the samples changed between the two chambers, the change in RH was compared to what the psychrometric process (method to determine moist air properties at known states and determine properties at an unknown state after a defined change from a known state), predicts the change in RH to be.

Typical RH change in the concrete samples was under 4% RH after either an increase or decrease in an ambient temperature of 5.5°C (10°F). The psychrometric process predicted that the concrete RH would change between 20% - 40% RH after the ambient temperature changed by

5.5°C. Psychrometric properties were not able to full describe the behavior of air in concrete pores so a new model was created to better predict the change in concrete RH after a change in ambient temperature. The developed model was able to predict concrete RH change within 5% error over the range of tested temperatures.

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## **Chapter 1: Introduction**

The use of concrete floor systems in residential construction have increased in popularity over the last couple of decades, and most of these systems receive a covering or coating (Kanare 2008). Floor coverings that are sensitive to moisture can become an issue during the life of the building. Water is a key component of concrete, and moisture from the concrete may cause moisture related issues in the coverings. The moisture related issues include delamination, buckling, mold growth, and others. Moisture from concrete is responsible for over \$1 billion in damages annually in floor covering failures (Armstrong 2012).

Concrete begins drying the second it is placed. The length of time required for moisture emissions to reach a non-damaging level can vary from a few weeks to several months, depending on a number of factors. However, construction practices often prevent contractors from waiting the appropriate amount of time before installing floor coverings, as an increase in fast-track construction processes prevent flexibility in the project schedule (Suprenant 1997). Recent environmental regulations have also contributed to increased moisture problems. Restrictions on emissions of volatile organic compounds (VOCs) have led to changes in adhesives forcing producers to rely more on water-based adhesive formulations, which are more sensitive to moisture, and may increase the rate of flooring failures (Suprenant 1997). Flooring manufacturers have taken steps to reduce the effects of concrete moisture by mandating installers measure the moisture conditions before installing floor coverings. Two of the main test methods used to measure concrete moisture conditions are the moisture vapor emission rates (MVER) test and the relative humidity (RH) test. Each of the two test methods has distinct advantages and disadvantages.

The MVER test, typically the anhydrous calcium chloride test, is widely accepted by flooring manufacturers to determine adequate concrete moisture levels (Armstrong 2012). Calcium chloride tests measure the moisture emissions from the concrete by sealing a dish of anhydrous calcium chloride under a plastic dome. The difference in the weight of the dish before and after testing allows the user to calculate the emissions from the concrete. Calcium chloride tests are easy to administer, and the results are easy to interpret. However, calcium chloride tests only measure conditions near the surface, generally the top ½ in. to ¾ in., while the conditions deeper in the slab are unknown (Kanare 2008). The surface moisture conditions will change after the concrete is covered; this change in conditions is not accounted for by the calcium chloride test (ACI 2006). The tests are also very susceptible to changes in ambient relative humidity and temperature. As such, ASTM 1869 for calcium chloride tests restricts the testing conditions to be conducted at  $23.9\pm 5.5^{\circ}\text{C}$  ( $75\pm 10^{\circ}\text{F}$ ) and  $50\pm 10\%$  RH (ASTM F1869 2015). Even within this allowable range the results from the calcium chloride tests can be affected by both temperature and humidity.

RH probes measure the relative humidity of the air in the pores of the concrete, and are accurate to a 2% tolerance and can be calibrated by the user with a check-salt solution (Tramex 2014). Relative humidity is the actual amount of moisture in the air compared to the amount of moisture that the air could hold if saturated, expressed as a percent (ASTM F710 2015). The amount of water the air can hold is dependent on temperature. If the temperature decreases, the relative humidity increases since the moisture carrying capacity of the air decreases. The magnitude of relative humidity change is calculated by the psychrometric process, which is the method to determine moist air properties at known states and determine properties at an unknown state after a defined change from a known state (Albright 1990). Psychrometric charts

are available to calculate the change in RH due to a change in temperature; however, these charts apply to atmospheric conditions and may not be able to accurately describe the behavior of water within the concrete pores. Despite that RH changes with a change in ambient temperature, ASTM F710-11 does not restrict the acceptable testing range for conducting RH tests (ASTM 2015a).

There is a lack of understanding about the influence of temperature on concrete moisture tests, especially RH and MVER tests. Even though ASTM restricts the ranges on calcium chloride tests, the variance in the tests within the allowable range is still large. ASTM has not taken the same precautions for RH tests, even though psychrometric properties predict RH can change by as much as 50% for each 10°C change in temperature (Gatley 2013). By taking measures to ensure one-sided drying when creating the samples, it is possible to make small-scale concrete samples behave similar to full-scale slabs. The small-scale tests can then help develop new models that better predict concrete behavior after a change in temperature.

### **1.1 Goals and Objectives**

The goal of this research was to examine how ambient temperature differences affect moisture emissions and RH measurements in concretes with a water-cement ratio of 0.6. Small scale specimens subjected to regulated temperature will be cast. Care will be taken so that the small scale samples simulate large scale slabs. A relationship will be developed to predict RH measurements at varying ambient temperatures.

Objectives:

- 1) Measure RH and MVER of low strength concrete samples under both cyclic and constant temperatures.

- 2) Create moisture profiles and drying curves to determine diffusion patterns under varying ambient and subsurface temperature conditions based on measurements from objective 1.
- 3) Compare small scales tests to large scale drying models to understand effect of temperature changes

## **1.2 Significance**

By achieving the research objectives, general contractors, flooring installers, and flooring manufacturers will be able to quantify in the field how changes in temperature affect their moisture results, and how to properly apply corrections. This research will give the industry a better understanding of the moisture emissions of concrete to determine if floor coverings can be applied. An indirect observation of this research will help explain why slabs can measure the same RH and have differing MVER results.



## Chapter 2: Literature Review

### 2.1 How concrete dries

Concrete dries in two processes; the first is a process known as self-desiccation, where mix water is consumed over time through cement hydration. The second process is evaporation of mix water at the surface of the concrete (Holmes & West 2013). Self-desiccation is the hydration of cement, and results in most of the drying in concrete's early stages. However, in concretes with high water-cement ( $w/c$ ) ratio ( $w/c \geq 0.68$ ) the drying effect of self-desiccation can be ignored (Kim & Lee 1999). After the cement has hydrated there are still significant amounts of mix water remaining in the capillary pores and the concrete continues to dry through the surface evaporation of water (Holmes & West 2013). The excess mix water reaches the concrete surface through a process known as diffusion.

#### 2.1.1 Diffusion in Concrete

Both Pickett (1942) and Brewer (1965) noted that the permeability of concrete decreased as the concrete aged and that the permeability of concrete increased as the  $w/c$  ratio increased. Pickett (1942) also noticed that the drying of concrete was much slower than a linear model with respect to time could predict. Pickett then proposed to assume the diffusion coefficient decreases during the period of drying. However, Pickett's assumption was determined to not be acceptable since a material property was then dependent upon an arbitrary point in time of concrete exposure (Bazant & Najjar 1971). The next assumption considered the diffusion coefficient associated with either the specific water content or the pore humidity (Bazant & Najjar 1971). Pore humidity was used since, "Pore humidity is the more suitable variable since [pore humidity] (unlike [specific water content]) is directly related to the Gibbs' free energy per unit mass of evaporable water,  $\mu$ , whose gradient is the actual driving force of diffusion" (Bazant & Najjar

1971, p 463). The model proposed by Bazant and Najjar for calculating concrete diffusion coefficients in 1971 was adopted by the CEB-FIP Model Code and is shown in Equation 2-1 (CEB & FIP, 1990). Equation 2-1 is able to accurately model the concrete diffusion coefficient for non-linear models. The maximum value for the diffusion coefficient,  $D_1$ , is from documented diffusion coefficients for varying  $w/c$  ratio.  $H$  is the internal RH of the concrete, and  $D(H)$  is the concrete diffusion coefficient at the specific RH.

$$D(H) = D_1 \left[ \alpha + \frac{1-\alpha}{1 + \left[ \frac{1-H}{1-H_c} \right]^n} \right] \quad [2-1]$$

Where:

$D_1$  is the maximum of  $D(H)$  for  $H = 1$  ( $m^2/s$ )

$D_0$  is the minimum of  $D(H)$  for  $H = 0$  ( $m^2/s$ )

$\alpha = D_0/D_1 \approx 0.05$

$H_c$  is the relative pore humidity at  $D(H) = 0.5D_1 \approx 0.80$

$n \approx 15$

While  $D$  is still dependent on ambient temperature and humidity, the internal RH of the concrete is still the main influence (West & Holmes 2005). Equation 2-1 is shown graphically in Figure 2-1. The diffusion constant,  $D$ , is constant until the RH drops to approximately 85%, then  $D$  decreases rapidly until 75% RH, where  $D$  remains constant thereafter. Higher  $w/c$  ratios result in a higher  $D$  values (West & Holmes 2005). The trend in Figure 2-1 applies to the drying of concrete mix water, not dry concrete that has been re-wetted.

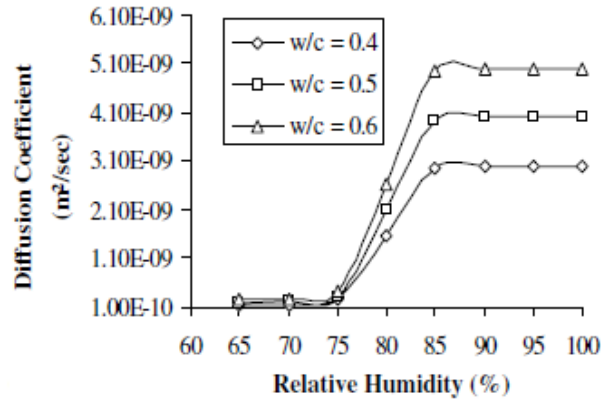


Figure 2-1: The Change of Diffusion Coefficients as RH changes for varying w/c ratios (West & Holmes 2005)

West & Holmes (2005) then used the values of  $D$  from Figure 2-1 to develop a finite element model (FEM) that can accurately predict concrete drying. By using the diffusion coefficient in Fick’s second law, which is shown in Equation 2-2 and has been accepted to represent the movement of moisture in concrete, the finite element model can predict the movement of moisture in concrete.

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial x} \left( D(H) * \frac{\partial P}{\partial x} \right) \quad [2-2]$$

Where:

- $D(H)$  is the diffusion constant ( $m/s^2$ ) as a function of the internal RH
- $P$  is the internal RH
- $x$  is the depth in the slab

### 2.1.2 Evaporation from Concrete

Water is removed from concrete through evaporation at the surface. Evaporation occurs at the surface of the concrete through a difference in RH between the surface of the concrete and the ambient conditions. Evaporation will stop once the RH gradient ceases to exist. At this time the concrete can be considered “dry” (Holmes & West 2013). Even though the RH gradient drives the process of evaporation, the rate of evaporation depends on physical characteristics,

including the ambient RH, ambient temperature, wind, surface finish, degree of hydration, and the presence of moisture suppressants (Holmes & West 2013). The combination of these factors are shown in Equation 2.3 which predicts the mass flux of moisture through the concrete surface,  $J$  (West & Holmes 2005)

$$J = K * (\phi_B - \phi_E) \quad [2-3]$$

Where:

- $K$  = convection coefficient dependent on the physical properties
- $\phi_B$  = Boundary RH of the concrete
- $\phi_E$  = Environmental RH

Using this equation, West & Holmes (2005) calculated the surface evaporation rates for the two situations used in their testing; a laboratory where ambient temperature and RH averaged 14°C and 55%, and an insulated room under permanent forced heating and a dehumidifier where average conditions were 27°C and 35% RH. At Day ( $d$ ) 0, the RH at the surface of the concrete was at 100% for both ambient conditions, and the humidity gradient at Day 0 for laboratory conditions was 45% and for the controlled room was 65%, both gradients decreasing as time increases. The results are shown in Figures 2-2a and 2-2b.

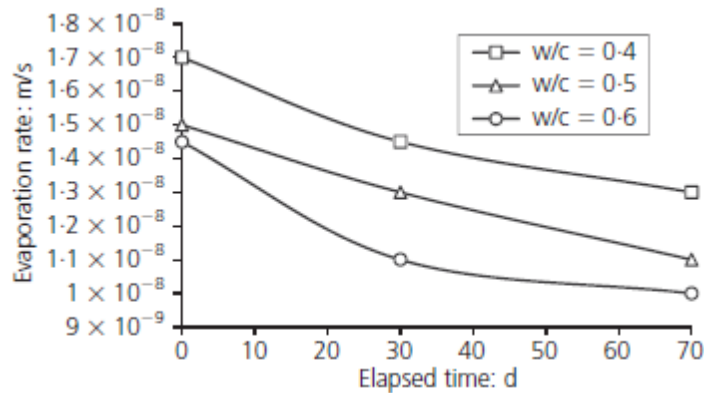


Figure 2-2a: Evaporation Rate in Laboratory Conditions, 14°C and 55% RH (Holmes & West 2013)

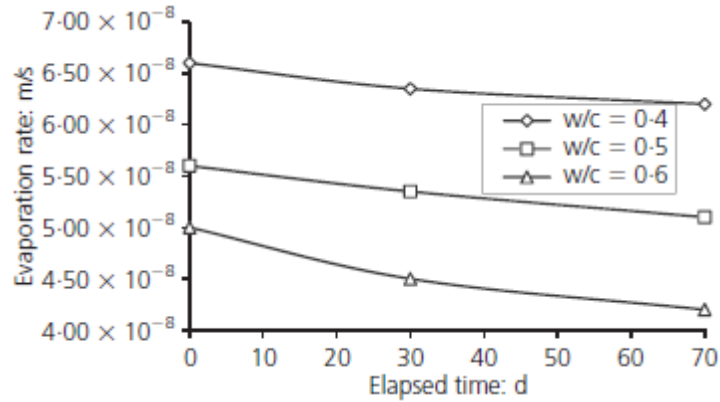


Figure 2-2b: Evaporation Rate in Controlled Room, 27°C and 35% RH (Holmes & West 2013)

The conditioned room had higher evaporation rates, due to both the higher humidity gradient, and the increased temperature. Lower  $w/c$  ratios also resulted in higher evaporation rates for the concrete. The evaporation rate decreased with time for all  $w/c$  ratios in all room conditions as the humidity gradient for the concrete decreased.

### 2.1.3 Complete Drying Models

Using the diffusion and evaporation models developed in Sections 2.1.1 and 2.1.2 respectively, West & Holmes (2005) developed a finite element model (FEM) that can predict the drying of concrete under different ambient conditions. Holmes and West used the software package DIANA, with the model using 700 eight-noded quadrilateral elements for diffusion and 70 two-noded elements at the surface for evaporation. The results of the FEM for a  $w/c$  ratio of 0.6 and a depth of 150mm (5.9 in.) are compared to experimental data at the conditions in the laboratory (Figure 2-3a) and the controlled room (Figure 2-3b). The legend in the bottom left of each figure shows the line styles used for the experimental (exp) and finite element analysis (FEA) results. The number before each label was the day that measurements were taken on.

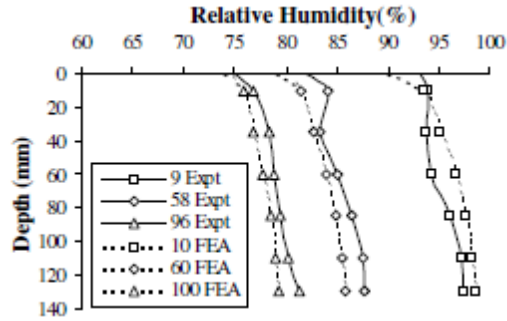


Figure 2-3a: Comparison of Finite Element Model to Experimental data in laboratory conditions  
14°C and 55% RH (West & Holmes 2005)

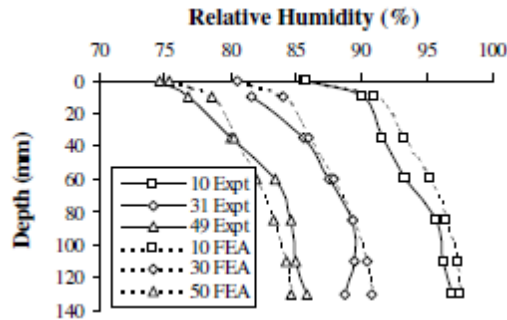


Figure 2-3b: Comparison of Finite Element Model to Experimental data in the controlled room,  
27°C and 35% RH (West & Holmes 2005)

The drying profiles of the experimental data and the model data were near matches at all ages of concrete. Any difference between the experimental data and model was less than 6% RH (West & Holmes 2005). Note the shapes that the drying profiles take. The laboratory condition samples (lower ambient temperature, higher RH) had a more linear profile, while the controlled room samples (higher ambient temperature, lower RH) had a curved profile. The surface conditions in the controlled room were much drier than the laboratory. At a depth of 0 mm, the controlled room had an RH of 85% at Day 10, while the laboratory had an RH greater than 90%. Even though the surface conditions were very different, conditions in the bottom of the concrete

wer very similar; both the samples in the controlled room and laboratory had RH measurements of 95% at a depth of 130 mm.

This trend continues to the measurements taken around Day 50 (Day 49 for controlled room, Day 58 for laboratory); the surface conditions for the samples in the controlled room were far drier than the laboratory conditions while the RH deeper in the samples was close to the same.

## **2.2 Drying in the Concrete Pores**

The rate of mass transfer through a porous solid, in this case moisture diffusion through concrete, is influenced by the material pores. The components of concrete contribute to the pore system, with the  $w/c$  ratio having the largest impact (Hearn et al 1994). As the concrete hydrates, the pore structure of the cement paste changes. Two classes of pores are formed in concrete, gel pores and capillary pores (Hearn et al 1994). Gel pores are between 1 and 2 nm in size and contribute little to the permeability of concrete, as water molecules have a greater affinity to the gel surface. Capillary pores are larger (10 nm to 5  $\mu\text{m}$ ), and when combined with micro cracks formed from drying, constitute the porosity of concrete. The initial pore structure of concrete is determined by the  $w/c$  ratio, with greater  $w/c$  ratios having a greater permeability. As the concrete ages and the degree of hydration progresses, new solids generated by hydration begin to fill the initial pores reducing the permeability of the concrete (Hearn et al 1994). Even after full hydration, concrete with high  $w/c$  ratio will not be able to fill the capillaries leaving the pore system continuous, creating paths for moisture migration (Hearn et al 1994). Experiments conducted by Brewer in 1965 corroborate the findings by Hearn.

The samples for Brewer's experiment consisted of 4 in. thick concrete slabs, with  $w/c$  ratios between 0.4 and 1.0 at 0.1 intervals, cast in the bottom of water tight paint cans measuring

6-1/2 in. in diameter by 7 in. high. The cans were coated with an epoxy sulfide compound to ensure a good seal, and the concrete was poured soon after. After a 7 day cure, the bottom of the cans was cut off so the surface of the concrete was exposed. A bead of epoxy resin was added around the rim to ensure a seal.

Some of the cans had the lids sealed on with no water added so water loss due to drying of mix water could be measured; the other cans were partially filled with water before having their lids sealed. Half of the water-filled cans were stored on grids with the exposed concrete down so that water was in direct contact with the concrete, with the other half stored concrete up so that the bottom of the concrete was only exposed to water vapor. Figure 2-4 below shows how the samples were oriented and location of the material. All of the samples were stored in a controlled room set to 22.8°C and 50% RH and outflow was measured by weighing the samples.

The results of Brewer's experiment are shown in Table 2-1; units for the table are grains/hour/square foot. Assuming Hearn's predictions about the concrete pore structure are true, the samples with higher  $w/c$  ratios should have significantly higher emission values than the samples with lower  $w/c$  ratios. The open pore structure due to the higher  $w/c$  ratio allows for an increased moisture migration in the concrete, confirming Hearn's predictions (Hearn et al 1994). The emissions rate increases with an increase in  $w/c$  ratio. A  $w/c$  ratio of 1.0 has ten times the emission rate of a  $w/c$  ratio of 0.4 throughout the experiment.



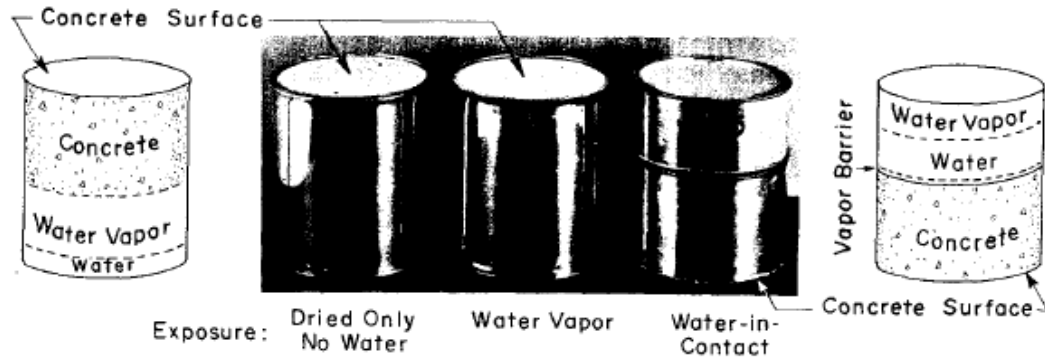


Figure 2-4: Set-up used by Brewer to measurement moisture migration (Brewer 1965)

Table 2-1: Moisture Migration of Concretes (Brewer 1965)

Days	Exposure	Moisture Migration (grains/hr/sq ft) at w/c ratios shown						
		w/c =0.40	0.50	0.60	0.70	0.80	0.90	1.00
3	W*	4.8	7.8	11.6	20.4	27	33	43.8
	WV	5	8	11.5	17	21	24.4	27.2
	D	5.2	8	11.4	16.5	19.2	27.2	22.8
7	W*	2.9	4.7	7.7	11.8	16.4	21.5	27
	WV	3	4.8	6.7	8.4	9.8	11	12.4
	D	3.1	4.6	6.1	7.6	9	10.2	11.5
14	W*	1.8	3	5	8.1	11.1	14.4	18.2
	WV	1.8	2.9	3.9	4.8	5.6	6.3	6.8
	D	1.9	2.8	3.7	4.6	5	5.5	6
28	W*	1.2	1.9	3.3	5.3	7.5	9.9	11.8
	WV	1.1	1.8	2.9	3	3.4	3.6	3.8
	D	1.1	1.7	2.3	2.6	2.8	3	3.2
60	W*	0.8	1.3	2.2	3.4	4.7	6.1	7.4
	WV	0.8	1.2	1.6	2	2.2	2.4	2.5
	D	0.7	1.1	1.3	1.5	1.6	1.7	1.8
90	W*	0.7	1.1	1.9	2.9	3.8	5	6
	WV	0.7	1	1.4	1.7	1.8	1.9	2.1
	D	0.5	0.8	1	1.1	1.2	1.3	1.4
180	W*	0.5	0.9	1.5	2.2	3	3.9	4.8
	WV	0.5	0.8	1.1	1.3	1.4	1.4	1.5
	D	0.3	0.5	0.6	0.6	0.7	0.8	0.9
365	W*	0.4	0.7	1.3	1.9	2.5	3.3	4.1
	WV	0.4	0.6	0.9	1	1.1	1.1	1.1
	D	0.2	0.3	0.4	0.4	0.5	0.5	0.5

W\* = water in contact

WV = water vapor in contact

D = drying only

The higher  $w/c$  ratios not only allow for increased moisture migration, but increased drying time as well. The higher emission rates at the early stages of drying are almost solely from the drying of concrete mix water, and concretes with higher  $w/c$  ratio have more mix water (Brewer 1965). A later analysis by Suprenant (1997) determined that, when exposed to drying only, an increase in concrete  $w/c$  ratio between 0.4 to 0.5 caused drying time to increase 73%, from 0.5 to 0.6 an increase of 48%, and above 0.6 an increase of 13%.

As predicted by Hearn, the ability for moisture to move through the concretes also decreased with age. Moisture migration was determined by subtracting the rate of drying in the drying only condition from the rate of drying in the water in contact condition. At the 365 day mark, the concretes ability to move moisture was about 25% of its ability at Day 3 (3.6 grains/hr/sf compared to 21 grains/hr/sf) (Hearn et al 1994).

### **2.3 Stages of Drying**

Concrete undergoes three stages of drying: the constant rate period (CRP), the first falling rate period (FFRP), and the second falling rate period (SFRP) (Scherer 1990). During the CRP, the rate of evaporation per unit area is constant with respect to time. The CRP begins after any covering used for moist curing the concrete has been removed, and there is liquid water on the surface of the concrete (Kanare 2008). The rate of evaporation is proportional to the difference between the liquid vapor pressure and the ambient vapor pressure, with the proportionality constant dependent on temperature, wind, and shape of the system (Scherer 1990). As the water evaporates, horizontal diffusion homogenizes the boundary layer as long as the dry patch is small compared to the thickness (Scherer 1990).

Once dry patches have become too large for horizontal diffusion to keep a film of liquid on the surface the water enters the pores and the FFRP begins. During this period, the rate of

evaporation decreases but is still dependent on the ambient temperature and vapor pressure (Scherer 1990). Most of the evaporation occurs at the surface from fluid flow, but some liquid evaporates in the unsaturated pores and is then transported by diffusion (Scherer 1990). Eventually flow to the surface stops and the SFRP begins. Now liquid is removed from the concrete only by the diffusion of vapor, the surface temperature approaches the ambient temperature, and the rate of evaporation becomes less sensitive to external conditions (Scherer 1990). Since in Equation 2.3 the ambient conditions, represented by  $K$ , have a large effect on the drying of concrete it can be concluded that concrete remains in the FFRP, and never loses enough water to enter the SFRP.

## **2.4 Measuring Concrete Moisture**

### **2.4.1 MVER**

MVER tests are the most common tests used in the United States to assess the moisture condition of concrete slabs. ASTM F1869 *Standard Test Method for Measuring Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride* controls the set-up and appropriate ambient temperature and humidity conditions for MVER tests (ASTM 2015b). Calcium chloride tests have been heavily used in the flooring industry to set emission levels for product warranties, and are the current test method recommended by the Resilient Floor Covering Institute (1995) and the Carpet and Rug Institute (2002) to measure concrete moisture (Kanare 2008).

Calcium chloride tests work by sealing an open container of anhydrous calcium chloride under a plastic dome. The moisture emitted by the concrete is trapped under the dome and then absorbed by the calcium chloride. The dome and container are left on the slab for 60-72 hours and the container is weighed immediately after removal. The weight of the container before the

test begins is subtracted from the weight after removal and is then multiplied by a coefficient (118.932/[Total Hours on Slab]) to determine the emission rate. The results from the test are expressed as pounds of moisture emitted from 1000 square feet in 24 hours (ASTM F1869). Typical limits set by the flooring industry are 3-5 lbs/1000 sq ft/24 hrs (Kanare 2008).

The MVER tests are easy to administer and cheap; however there are a number of deficiencies in them that can affect results. The tests were first developed as a qualitative evaluation tool in the 1940s before becoming a quantitative test in the 1960s (Kanare 2008). There is no published data available from this time period that explains how parameters, like kit dimensions, time of exposure, choice and mass of desiccant, and basis for calculations, were developed (Kanare 2008). This lack of data and a lack of a reference concrete with controlled MVER levels mean there is no practical way to calibrate MVER test kits (Kanare 2008).

MVER tests only measure moisture conditions in the top ½ in. to ¾ in. of the slab, and the conditions deeper in the slab are unknown (Kanare 2008). After the slab is covered, the surface conditions of the slab will change and the results from the previously administered test no longer represent the conditions in the surface of the concrete (ACI 3022R 2006). If the test is used on a slab that is covered by an impermeable covering, the results can be artificially higher than an uncovered slab, since moisture is being forced to evaporate only through the test area.

MVER testing is sensitive to the ambient conditions of the testing environment. ASTM F1869 restricts the allowable ambient temperature to 18.3°C – 29.4°C and RH to 40% - 60%, however research has shown that the test results can vary within these ranges (Kanare 2005). Suprenant (2003) examined the use of correction factors for calcium chloride tests conducted under different ambient RH conditions. Suprenant determined that in the range of interest (3-5 lbs/1000 sf/24 hrs) the RH under the sealed dome when the test started was not different than the

RH when the test ended so no correction factor was needed for ambient RH levels (ACI 302.2R 2006). Kanare (2005) examined how different temperatures, within the allowable ASTM range, affect the MVER results of concretes. Kanare used w/c ratios of 0.4, 0.5, 0.6, and 0.7 in his study, and the results are shown in Figure 2-5.

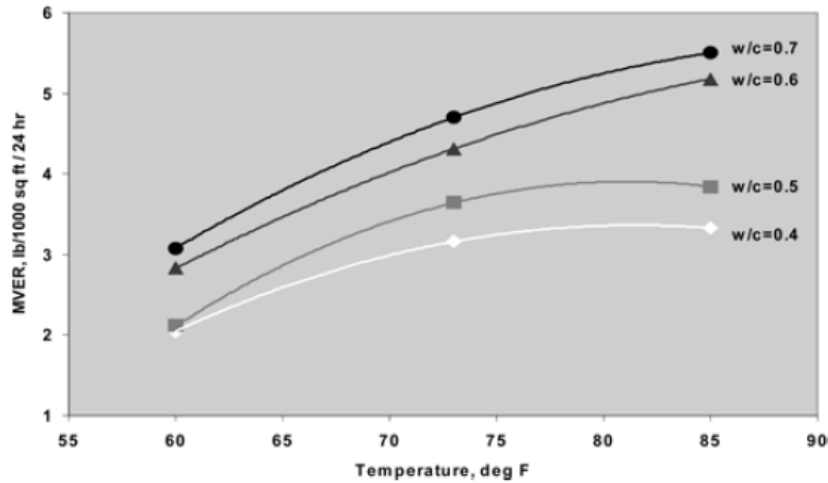


Figure 2-5: Effect of temperature on calcium chloride tests for different concretes (Kanare 2005 ACI 302)

All w/c ratios showed an increase in moisture emissions, with the higher w/c ratio having a greater increase as temperature increases (Kanare 2005). Despite these results, no correction factor for the acceptable temperatures in calcium chloride tests has been published.

### 2.4.2 Relative Humidity Tests (RH)

Relative humidity tests are another common test used in the industry. Other countries, including Great Britain and New Zealand, use RH tests as an industry standard (Kanare 2008). The British standard for the tests, BS5325 and BS8203, use a hygrometer under a sealed plastic dome on top of the concrete to measure the RH of the air under the dome (Kanare 2008). While slightly more reliable than the MVER tests, this form of RH tests still have some of the

disadvantages of the MVER test. The RH is susceptible to changes in ambient RH and temperature, and has a limited effective depth.

In 2002, ASTM approved a new RH test, ASTM F2170 *Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes*, which is less susceptible to changes in ambient temperature and RH (Kanare 2008). For drying allowed only on the top surface, the most common condition in American construction, the test requires an RH probe be placed at 40% of the slab depth (ASTM 2015c). Forty percent is the depth in the slab where the RH before the covering is placed is equal to the RH after the covering is placed, and the phenomenon is shown in Figure 2-6

An RH measurement at 40% depth can predict the RH of a covered slab. After a low-permeability covering is placed over top of the slab, moisture emissions from the slab become zero. Even though moisture emissions are now zero, there is still a humidity gradient (line B) within the slab, as the top is drier than the bottom. Diffusion continues to occur in the concrete until there is no longer a humidity gradient along the slab depth (line C). Research has determined that the equilibrium RH for the slab is found at 40% depth for one-sided drying (intersection of lines B and C) (ACI 2008).

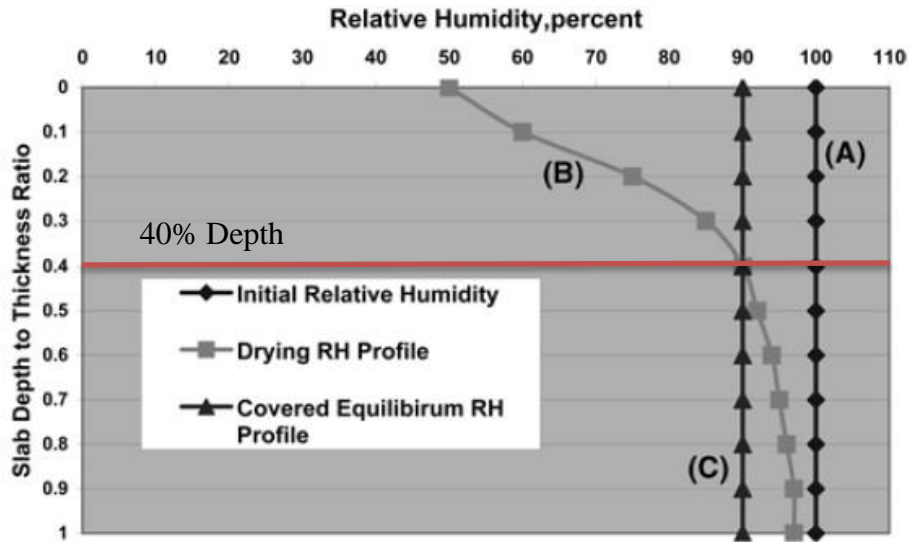


Figure 2-6: Approximate RH profiles of concrete before (Line B) and after (Line C) a low-permeability covering is placed (ACI 2008)

To take the measurements at the 40% depth, a hole is either drilled in the set concrete and a tube compliant with ASTM F2170 is placed in it, or the ASTM approved tube is placed in the concrete before it becomes set. The tube creates a small sealed environment that after a period of 72 hours will reach moisture equilibrium with the surrounding concrete (ASTM 2015c). Once the initial 72 hour wait period has been satisfied, measurements will be representative of the surrounding concrete moisture conditions provided the RH probe is at the same temperature as the concrete. The tube placement and fit of the hole and the location of the sealed measuring environment are shown in Figure 2-7 (ASTM F2170).

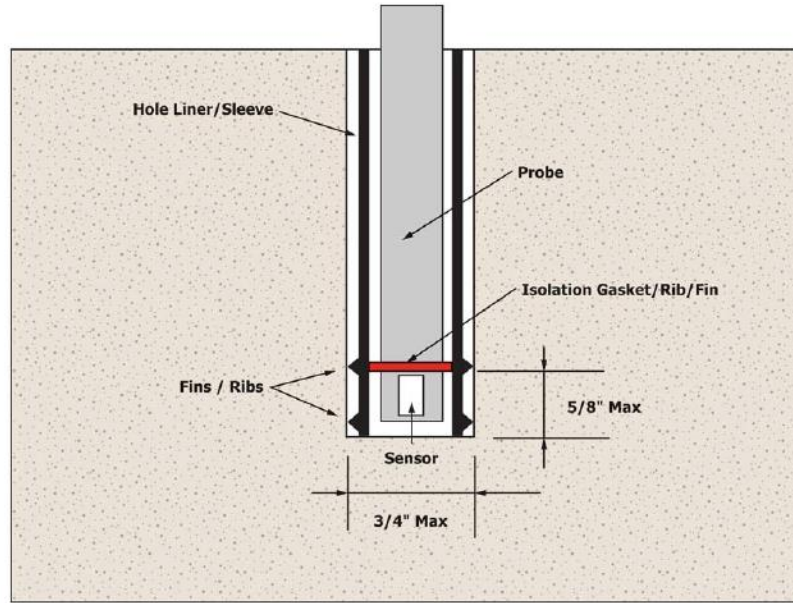


Figure 2-7: Example of RH Probe (ASTM 2015c)

ASTM F2170 RH tests are more accurate than other concrete moisture testing methods, however still have some of the same deficiencies as other testing methods. Measurements can still be affected by ambient temperature and RH, and ASTM F2170 has no restriction on acceptable ranges for ambient temperature and RH needed for testing (ASTM 2015c). Researchers have developed correction factors that account for ambient conditions.

The Swedish Concrete Association (SCA) tested a series of concrete slabs, similar to Brewer's work, to examine how different conditions affect concrete drying time (Kanare 2008). The SCA developed a series of correction factors that account for various parameters of the concrete slab and ambient conditions. The correction factors, shown in Tables 2-2 through 2-5, can be used by contractors and flooring installers to calculate the amount of time needed for a slab to dry to an adequate level if the ambient conditions are known. These correction factors are applied to a standard drying time developed during the research, and looked at an internal RH at 40% depth, as mandated by ASTM F2170 (Hedenblad 1997). The factors were developed in a lab and can be used to estimate the drying time of concrete in any country (Hedenblad 1997).



Table 2-2: Standard Drying Time, Days

RH, %	w/c = 0.4	w/c = 0.5	w/c = 0.6	w/c = 0.7
85	50	90	135	180
90	20	45	65	95

Table 2-3: Correction Factors for Different Slab Thicknesses

Thickness, mm (in)	w/c = 0.4	w/c = 0.5	w/c = 0.6	w/c = 0.7
100 (4)	0.4	0.4	0.4	0.4
150 (6)	0.8	0.8	0.8	0.7
180 (7)	1.0	1.0	1.0	1.0
200 (8)	1.1	1.1	1.1	1.2
250 (10)	1.3	1.4	1.5	1.8

Table 2-4: Correction Factor for One-Sided or Two-Sided Drying

Dry Condition	w/c = 0.4	w/c = 0.5	w/c = 0.6	w/c = 0.7
One-sided	2.0	2.3	2.6	3.2
Two-sided	1.0	1.0	1.0	1.0

Table 2-5: Correction Factors for Temperature and Humidity

RH, %	10°C (50°F)	18°C (64°F)	25°C (77°F)	30°C (86°F)
35	1.2	0.8	0.7	0.6
50	1.2	0.9	0.7	0.6
60	1.3	1.0	0.8	0.7
70	1.4	1.1	0.8	0.7
80	1.7	1.2	1.0	0.9

While limited in their application, the preceding correction factors allow the user to understand how different conditions will affect the drying of the slab. Note that the ambient temperature has a larger effect on concrete drying than relative humidity (ACI 3022R 2006). An example has been run to show this effect.

### Drying Condition Scenarios

1. A 6 in. slab with a  $w/c = 0.6$  drying to 90% exposed to one-sided drying at 50% RH and 25°C
2. A 6 in. slab with a  $w/c = 0.6$  drying to 90% exposed to one-sided drying at 50% RH and 30°C
3. A 6 in. slab with a  $w/c = 0.6$  drying to 90% exposed to one-sided drying at 35% RH and 25°C

### Calculations

1.  $65 \text{ days} * 0.8 * 2.6 * .7 = 95 \text{ days}$
2.  $65 \text{ days} * 0.8 * 2.6 * .6 = 81 \text{ days}$
3.  $65 \text{ days} * 0.8 * 2.6 * .7 = 95 \text{ days}$

According to Equation 2-3, either a decrease in ambient relative humidity or an increase in temperature should increase the rate of drying, since the decrease in ambient RH increases the humidity gradient and the increase in ambient temperature increases the convection coefficient,  $K$ . A 5°C increase in ambient temperature causes the speed of concrete drying to decrease by 14 days, but the change in ambient relative humidity did not have the same effects. A 15% decrease in ambient RH, increasing the humidity gradient, at the same ambient temperature should increase the rate of drying. However the time the concrete would take to reach 90% RH remained constant at 95 days.

### 2.5 Psychrometric Process

The psychrometric process is the method to determine moist air properties at known states and determine properties at an unknown state after a defined change from a known state (Albright 1990). Assumptions for use include standard temperature and pressure at sea level

(15.0°C and 101,325 Pa), and the air and water vapor are assumed to act as perfect gases. Errors from these assumptions are generally less than 1% and many of the properties can be determined as long as two properties are known (Albright 1990). The most commonly recorded property is dry-bulb temperature, which is the temperature recorded by an ordinary thermometer. Using solely the dry-bulb temperature, the water vapor saturation partial pressure ( $p_{ws}$ ) can be calculated (Eq 2-4). The water vapor saturation partial pressure is the pressure of a vapor when it is in equilibrium with the liquid phase (Albright 1990).

$$(p_{ws}) = \frac{A_1}{T} + A_2 + A_3 * T + A_4 * T^2 + A_5 * T^3 + A_6 * T^4 + A_7 * \ln(T) \quad [2-4]$$

Where:

$$A_1 = -5.6745359 * 10^3$$

$$A_2 = 6.3925247$$

$$A_3 = -9.677843 * 10^{-3}$$

$$A_4 = 6.221570 * 10^{-7}$$

$$A_5 = 2.0747825 * 10^{-9}$$

$$A_6 = -9.484024 * 10^{-13}$$

$$A_7 = 4.1635019$$

T = dry-bulb temperature measured in Kelvin

Relative humidity ( $\phi$ ), the most common measurement for determining moisture levels in concrete, is the ratio of the actual partial pressure of water vapor in moist but unsaturated air ( $p_w$ ), to the saturated partial pressure ( $p_{ws}$ ) (Eq. 2-5). Both partial pressures are defined at identical temperatures and atmospheric pressures (Albright 1990). Relative humidity is often incorrectly defined as the mass of water present in the air to the greatest possible mass at the same temperature, unless the phrase “and the same volume” was added to it (Gatley 2013).

$$\phi = \frac{p_w}{p_{ws}} \quad [2-5]$$

Relative humidity,  $\phi$ , is the same quantity being measured by ASTM F-2170. The calculation of  $\phi$  is completed assuming that the vapor pressure of water in moist air is the same

as the amount of moisture in the air. By assuming that the air is an ideal gas, and that  $p_{ws}$  and  $p_w$  are measured at the same temperature, pressure, and volume, the vapor pressure of water in moist air does correlate directly to the amount of water in the air due to the ideal gas law (Albright 1990). However, the saturation partial pressure changes non-linearly with a change in temperature. As dry-bulb temperature increases, the amount of moisture the air can hold increases as well. Utilizing Equation 2-3, a plot of temperature vs saturation water vapor pressure is shown in Figure 2-8.

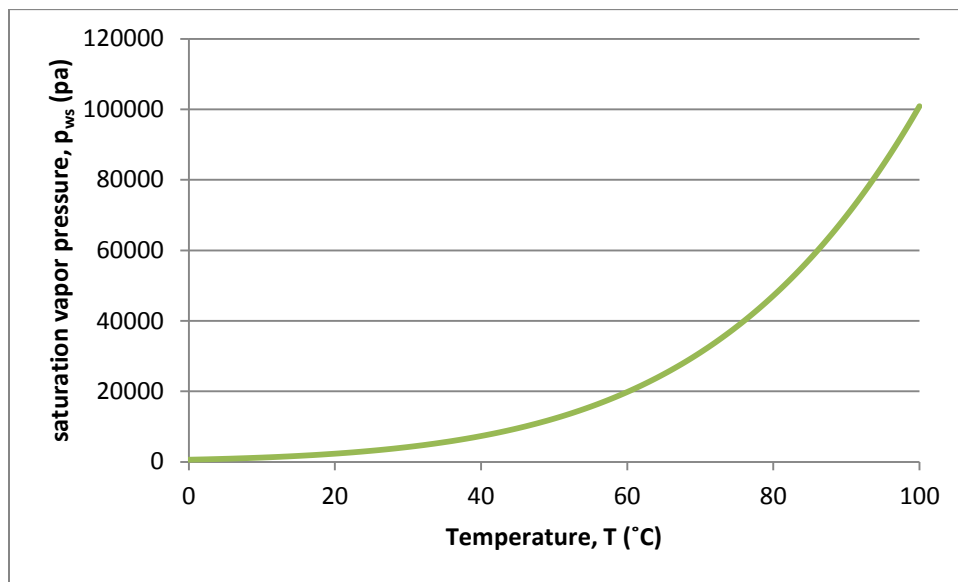


Figure 2-8: How saturation water vapor pressure ( $p_{ws}$ ) changes with a change in temperature

As sensible heat (heat that changes the temperature of a system) is added to the system, the amount of water vapor in the air does not change, and consequently  $p_w$  remains constant, unlike  $p_{ws}$ . Therefore, RH measurements change with a change in temperature as a non-linear function (Figure 2-9).

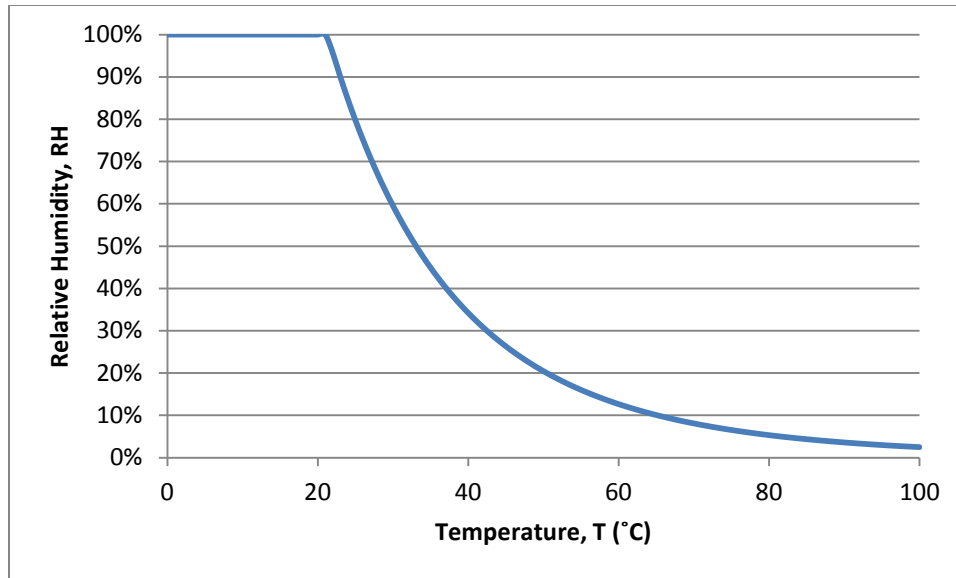


Figure 2-9: How relative humidity changes with a change in temperature

These properties of moist air are shown on the psychrometric chart (Figure 2-10), a tool often used in the field to graphically determine different properties of air. On the chart, dry-bulb temperature (temperature recorded by an ordinary thermometer) is shown along the x-axis, while the weight of water vapor per weight of dry air (humidity ratio) is shown along the y-axis. If relative humidity can consistently measure the amount of moisture in the air, the lines would be horizontal and independent of dry-bulb temperature. However, the relative humidity lines on the psychrometric chart are non-linear as well, indicating that the same RH measurements taken at different temperatures have different amounts of moisture in the air. The use of the psychrometric chart, and known equations, allow the amount of moisture in the air to be calculated. The psychrometric chart can be used to determine the amount of moisture in the air at different temperatures for the same relative humidity measurement (Figure 2-10).

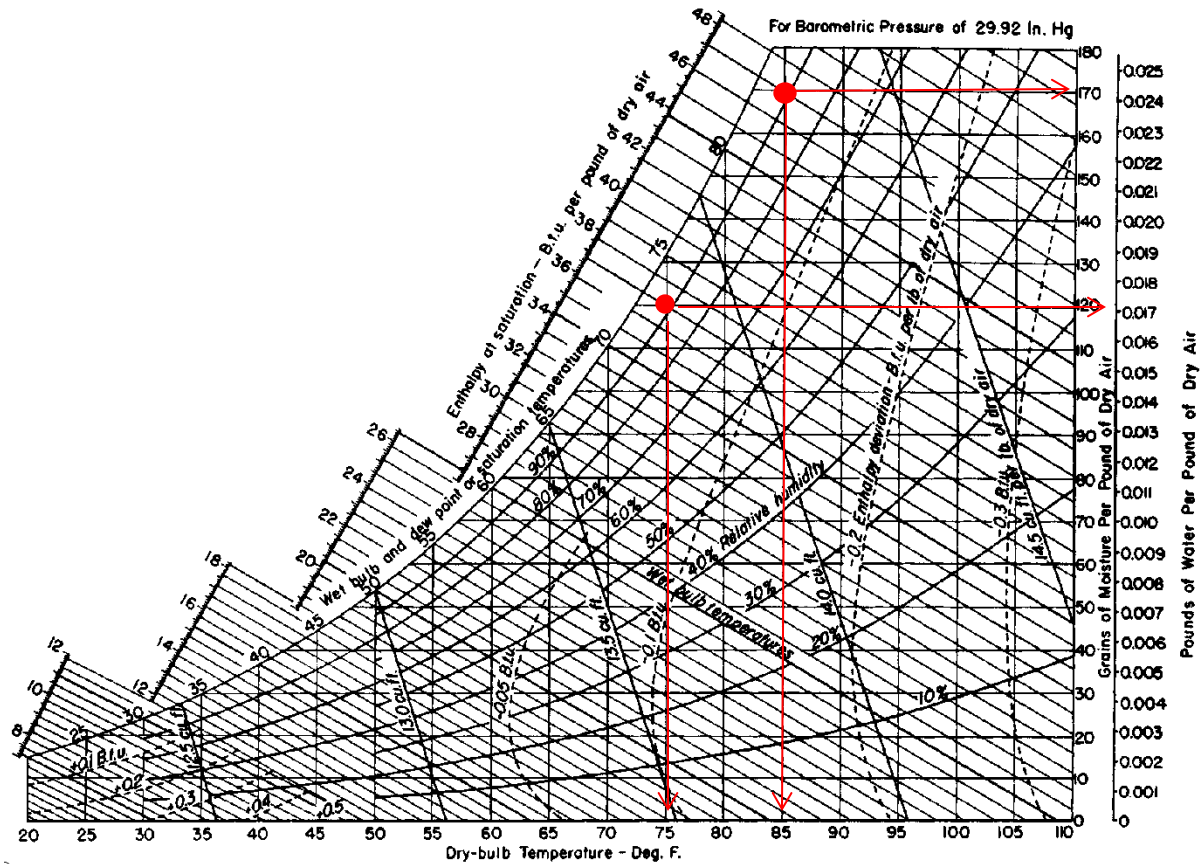


Figure 2-10: Psychrometric Chart (original source unknown)

From reading Figure 2-10, an increase from 23.9°C (75°F) to 29.4°C (85°F) at 90% RH increases the amount of moisture in the air from 0.0017 lbs water/lbs dry air to 0.0024 lbs water/lbs dry air. The amount of moisture in the air is also known as the humidity ratio, or mixing ratio, and can be calculated using Equations 2-5 (Albright 1990).

$$W = \frac{0.62198 \cdot x_w}{x_a} \quad [2-5]$$

$$x_a = \frac{p_a}{p} \quad [2-5a]$$

$$x_w = \frac{p_w}{p} \quad [2-5b]$$

$$p_w = \phi * p_{ws} \quad [2-5c]$$

$$p_a = p - p_w \quad [2-5d]$$

Where:

$$p = 101,325 \text{ pa (standard atmospheric pressure at sea level)}$$

The results from Equation 2-5 are very similar to that obtained from the psychrometric chart, as the humidity ratios for 23.9°C and 29.4°C are 0.0167 and 0.0234, respectively. The same pattern can be noted for consistent humidity ratios, as the RH measurement changes with temperature despite the amount of moisture in the air remaining constant. The relative humidity measurements at different temperatures do not have the same amount of moisture in the air, and as such RH measurements should not be treated the same at different temperatures.

## **2.6 Summary of Literature Review**

How concrete dries has been heavily studied, and there are models that can accurately predict concrete behavior under varying ambient conditions. The models use established diffusion and evaporation equations to develop concrete moisture profiles. However, very little research has been done to understand the effects of an immediate temperature change on the existing methods to test concrete moisture levels, despite understanding the effect ambient temperature can have on relative humidity and emissions.

## **Chapter 3: Materials and Methods**

This section discusses the materials and procedures used to examine how ambient temperature differences affect moisture emissions and RH measurements. Small scale samples that can simulate large scale slabs were created and exposed to two different ambient temperatures. Samples were switched between the regulated conditions at different intervals and underwent emissions and relative humidity testing in each condition.

### 3.1 Materials

#### 3.1.1 Concrete Samples

The mix design for the concrete was formulated using a  $w/c$  ratio of 0.6, Type I/II Portland Cement, and #57 coarse aggregate. The proportions for the mix are shown in Table 3-1 and scaled to produce 1 cubic foot of concrete. Approximately 3.66 cubic feet of concrete were required to fill all 12 samples. The mixer being used could only mix 1 cubic foot of concrete at a time so four batches were made. All four batches were the proportions shown in Table 3-1.

Table 3-1: Proportions for Concrete Mix Design

Material	Weight (lbs)
Coarse Aggregate	64.74
Fine Aggregate	54.74
Portland Cement	21.83
Water	13.10

The forms were 5 gallon plastic buckets, cut down using a band saw to a height of 6 in. After being cut, the buckets measured 10.5 in. in diameter at the top edge. At the completion of the curing process, silicone caulk was placed along the rim of the bucket to ensure a good seal between the bucket and the concrete. The caulk helps to simulate a full scale slab by sealing the concrete on five sides, only allowing for one-sided drying from the top of the sample.

Strength of the concrete was not measured. While concrete strength is the most important characteristic in the field, strength will have no impact on the drying of concrete. The concrete was cured for 1 week; the first 3 days the samples were covered with two layers of 4-mil plastic sheeting. The plastic was then removed for the final 4 days of the curing process.

Leave-in tubes needed to be placed in the concrete in order to measure RH in compliance with ASTM F2170 (Tramex 2014). Out of the package, the tubes measure 3.1 in. Before installation, the tubes needed to be amended to achieve the desired sizes of 1.2 in. (20% depth), 2.4



in. (40% depth), 3.6 in. (60% depth), and 4.8 in. (80% depth). To achieve the tube sizes shorter than 3.1 in. the top portion of the tube was cut off the appropriate amount. For tube lengths greater than 3.1 in., the portions cut off of the other tubes was placed on top of an uncut tube and wrapped in foil tape before being cut to the proper size. This was determined to be an adequate solution since the tubes need only keep concrete and moisture out of the testing area. Each tube was inspected before placing the sensor to ensure the area was clear of undesired moisture and concrete. Wooden dowels 7/16 in. in diameter were then placed in the tubes so that concrete did not flow into the testing area during curing.

### **3.1.2 Placing and Finishing the Concrete**

After the concrete was placed into the plastic buckets, the top of the bucket was compacted using a rod and finished with a hand trowel. The leave-in tubes for the RH probes were placed in the concrete, aligning the tops of the tubes even with the surface of the concrete. Each tube was placed 2 in. from the center of the sample (3.25 in. away from the edge), and were placed every 90 degrees around the sample. This spacing allowed for the maximum distance between tubes, ensuring no interference between measurements. After the tubes were placed, the concrete was once more compacted using a rod. The tubes did not need to be held in place during compaction; however the tubes were pushed back into the concrete as the concrete would cause the top of the tube to float slightly above the surface.

To obtain the desired spacing, an X-shaped device was created with holes in the appropriate spots for the tubes. A photograph of this device is shown in Figure 3-1, and the dowels sticking above the device represent the placement of the tubes.



Figure 3-1: Placement of tubes in wet concrete

The samples were allowed to dry in open laboratory conditions for 3 hours before being covered with two layers of 4-mil plastic. The plastic covered the samples for 3 days. Afterwards, the plastic was removed and the samples were allowed to cure for an additional 4 days. Once the 7 day curing period was over, the wooden dowels were removed from the tubes, and caps were placed on the tubes to seal the environment. The caps were labeled so the tube depth could be easily determined, with “2” representing a 20% depth tube, “4” a 40% tube, “6” a 60% tube, and “8” a 80% tube. After the caps were placed, silicone caulk was placed along the seam between the concrete and the form. A top of view of a sample is shown in Figure 3-2a, with a side view in Figure 3-2b.



(a)



(b)

Figure 3-2: (a) Top view of sample (b) Side view of sample

### 3.2 Monitoring Parameters

Tramex Hygro-I Probes were used to record the concrete temperature and relative humidity. Before use, the probes were calibrated in a salt check solution designed to provide a 75% RH environment. If the probes did not read 75% RH, the probes were not used in this study. Only five of the six probes qualified for this study due to this requirement. The probes are not leave-in probes, and need to be removed after recording the desired readings. The probes required a 10 minute period after being placed in the sleeves to acclimate to the temperature of the concrete. After 10 minutes, the temperature and RH were recorded. The probes were left in the tubes for another 5 minutes, and at the end of this time the temperature and RH were recorded again and compared to the measurements after the 10 minute period. The measurements after the total 15 minute period were accepted as final as long as four of the five probes measured no more than a 1% difference between the measurements at 10 and 15 minutes. If this criterion was not met, the probes were left in the tubes for an additional 2 minutes, 17 minutes total, before being tested again. This procedure was repeated until the criterion was met.

MVER tests were conducted during the first week of testing. Unfortunately, ASTM F1869 could not be strictly followed during testing, as the 20 in. x 20 in. surface area mandated for a calcium chloride test would make the samples extremely heavy and difficult to handle. Since all samples have the same surface area and same finish, comparisons between the samples would still be valid provided the same test methods were used. Equation 3-1 was used to calculate the moisture emissions from the MVER test (ASTM 2015 a). The contact area of the flanged cover on the concrete was 7 in. x 7 in., and the CaCl dish had a diameter of 2.75 in.

$$MVER = \frac{52.91 \cdot \Delta M}{A \cdot T} \quad [3-1]$$

Where:

$MVER$  = moisture vapor emission rate [lb/1000 sf/24 hrs]

$\Delta M$  = change in mass of anhydrous CaCl [g]

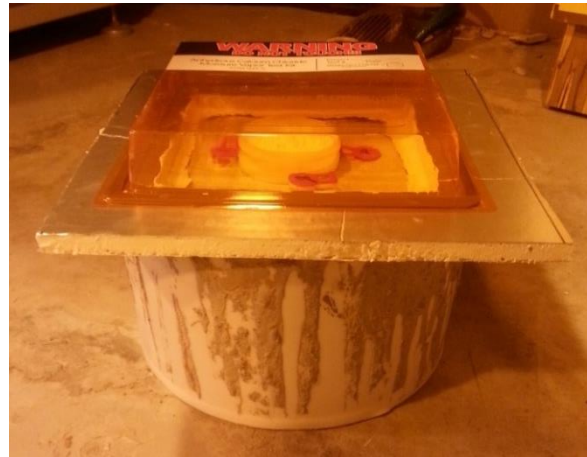
$A$  = contact area of the flanged cover on concrete deducting the area of the CaCl dish [ft<sup>2</sup>]

$T$  = exposure time [hours]

The domes used to conduct the calcium chloride tests were larger than the tests samples, and were not able to be properly sealed. To solve this, 10 in. x 10 in. pieces of Styrofoam insulation board were cut, each with a 7 in. x 7 in. hole in the middle. The domes were attached to the Styrofoam board using the sealing strips placed under the edges of the dome during manufacturing. After the calcium chloride test sample was placed on the concrete, silicone caulk was used to seal the board and dome to the concrete (Figure 3-3a and Figure 3-3b). The seal was considered sufficient when the top of the dome was pressed on it would not depress. ASTM F1869 procedures were followed for the remainder of the test (ASTM 2015 a).



(a)



(b)

Figure 3-3: (a) Top view of MVER Test set-up (b) Side view of MVER Test set-up

### 3.3 Temperature Variance

#### 3.3.1 Long-Term Drying

The samples were exposed to two different environments, 29.4°C and 23.9°C, both with an ambient RH of 50% and will be referred to as Chamber 1 and Chamber 2, respectively. The conditions were created by two different environmental chambers; A Cincinnati Sub-Zero P-16 created the warmer environment, and Parameter Generation Control (model#: 9135-8114DT) was used for the cooler environment. At the end of the 7 day curing period, half of the samples (Samples 1-6) were placed in Chamber 1. The other half (Samples 7-12) placed in Chamber 2. Over the next three weeks, RH and temperature measurements were taken at 0, 3, 6, 7, 10, 13, 14, and 24 days, with MVER tests placed on Day 3 and removed on Day 6.

After completing all of the measurements on Day 6, half of the samples in Chamber 1 (Samples 4-6) were removed and placed in Chamber 2, and half of the samples in Chamber 2 (Samples 7-9) were removed and placed into Chamber 1. The samples remained in this configuration for 1 week. On Day 13, after all RH tests were completed, Samples 4-6 were

switched back to Chamber 1, and Samples 7-9 were switched back to Chamber 2. Samples 1-3 and Samples 10-12 were the controls that remain in constant temperature. Samples 4-6 represented an increase in temperature then a decrease. Samples 7-9 represented a decrease in temperature then an increase. The testing matrix is shown in Table 3-2.

Table 3-2: Testing Matrix

Day	<b>0</b>	1	2	<b>3</b>	4	5	<b>6</b>	<b>7</b>	8	9	<b>10</b>	11	12	<b>13</b>	<b>14</b>	15-23	<b>24</b>
Sample 1-3				<b>MB</b>			<b>ME</b>										
Sample 4-6				<b>MB</b>			<b>ME</b>										
Sample 7-9				<b>MB</b>			<b>ME</b>										
Sample 10-12				<b>MB</b>			<b>ME</b>										

Key:

- Bolded Days: RH and Temp readings
- MB: Begin MVER test
- ME: End MVER test
- Diagonal Pattern: Samples in Chamber 2

### 3.3.2 Short Term Drying

After Day 24, the length of time the samples were allowed to equilibrate in the chambers to examine if shorter exposure conditions altered the results. Samples 1-6 started in Chamber 1, and Samples 7-12 began in Chamber 2. Approximately 24 hours after the Day 24 measurements were recorded, the samples were measured again. Immediately after RH testing, Samples 4-6 and Samples 7-9 were switched between Chambers 1 and 2. After 3 hours of equilibrating in the new chambers, all of the samples were tested. The samples were allowed to remain in the current chambers for another 24 hours before being tested for a final time. No MVER tests were conducted during the short-term drying tests since the samples were not at a constant temperature for the required 60 hour period. The testing matrix is shown in Table 3-3.

Table 3-3: Short-Term Drying Testing Matrix

<b>Day</b>	<b>24</b>	<b>25 AM</b>	<b>25 PM</b>	<b>26</b>
<b>Hour</b>	<b>0</b>	<b>24</b>	<b>27</b>	<b>48</b>
Sample 1-3	C1	C1	C2	C2
Sample 4-6	C1	C1	C2	C2
Sample 7-9	C2	C2	C1	C1
Sample 10-12	C2	C2	C1	C1

## **Chapter 4: Discussion and Results**

### **4.1: Examination of How Ambient Temperature Changes Affect Relative Humidity**

#### **4.1.1: Long Term Drying**

The results for temperature,  $T$  [ $^{\circ}\text{C}$ ], and relative humidity, RH, recorded at 20%, 40%, 60%, and 80% depths for long term drying are shown in Appendix A. The average for each sample grouping, 1-3, 4-6, 7-9, and 10-12, was used for comparison. The coefficient of variation for each sample grouping was below 5% for all RH and temperature measurements. From these results, an RH drying curve at 40% depth was plotted, and is shown in Figure 4-1a. The 40% depth was taken as the default depth for all tables and figures since this is the depth RH is measured at for one-sided drying. Temperature measurements are shown in the Appendix as well. Note that the temperature was similar across all depths of the samples; any variance is from the display on the probe since only two significant figures for temperature are shown.

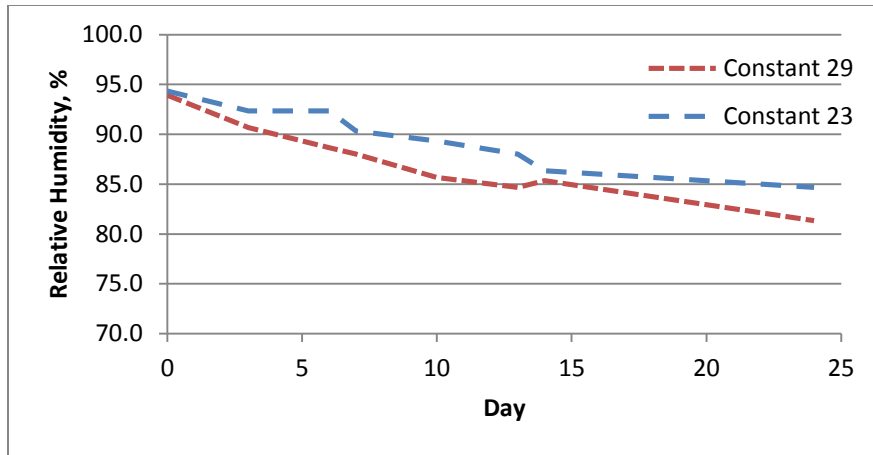


Figure 4-1a: Drying Curve for Days 0 to 24 at 40% Depth for Constant 29 and Constant 23

Between Days 0 and 24, Samples 1-3 and Samples 10-12 were exposed to constant temperatures of 29.4°F and 23.9°F, and will be referenced as “Constant 29” and “Constant 23”, respectively. Constant 29 had a mostly smooth drying curve dropping approximately 1% RH each day, but had an increase in RH from Day 13 to Day 14 of 0.6% RH. After the small unexpected jump on Day 14, Constant 29 continued drying at an expected rate of 0.5%/day until Day 24.

Constant 23 had a less consistent drying curve, having a drop of approximately 2% RH between Days 6 and 7 after having no decrease in RH between Days 3 and 6. Constant 23 again had an unexpected drop between Days 13 and 14. After drying at an average of 0.4%/day between Days 7 and 13, Constant 23’s RH measurement decreased by 1.7% over the 1 day period, before continuing to dry at a 0.16%/day rate from Day 14 to Day 24. While concrete drying is a non-linear process, the random increases and decreases in RH without a change in temperature are unexpected.

An examination of the drying profile at different depths in the samples show that the increases and decreases in RH found at 40% depth increase in magnitude at 20% depth (Figure 4-1b).



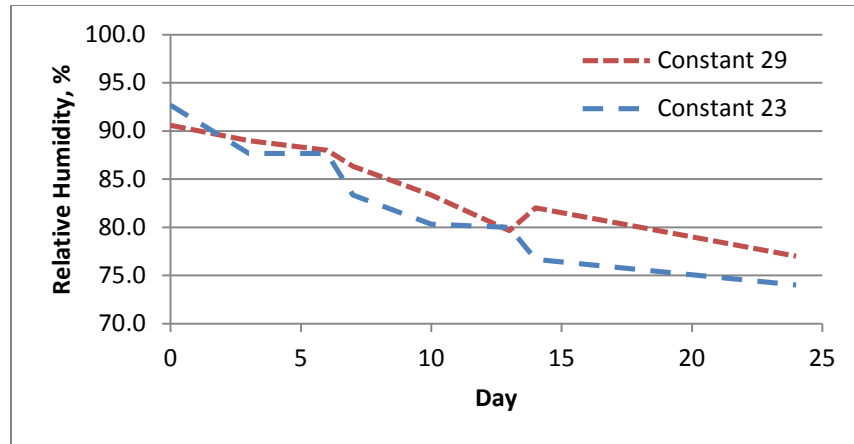


Figure 4-1b: Drying Curve for Days 0 to 24 at 20% Depth for Constant 29 and Constant 23

At 20% depth, the 0.6% RH jump in Constant 29 increased to a 2.3% RH increase between Days 13 and 14. Constant 29 dried at rates of 1.2%/day and 0.5%/day before and after the increase, respectively. The drop in RH of Constant 23 between Days 6 and 7 increased to a difference of 4.4% at 20% depth. The 4.4% drop in RH occurred after no decrease in RH the three days prior and only decreased at a rate of 1.0%/day afterwards. Between Days 13 and 14, the 1.7% RH drop in Constant 23 at 40% depth increased to 3.3% at 20% depth. Constant 23 dried at rates at 20% depth before Day 13 was 0.1%/day and after Day 14 was 0.27%/day. The slow rates of drying of Constant 23 before and after the increases make the drops at 20% depth between Days 6 and 7 and Days 13 and 14 more prominent than at 40% depth. This trend continues at 60% (Figure 4-1c), where the drying curve flattens as the increases and decreases in RH decrease in magnitude.

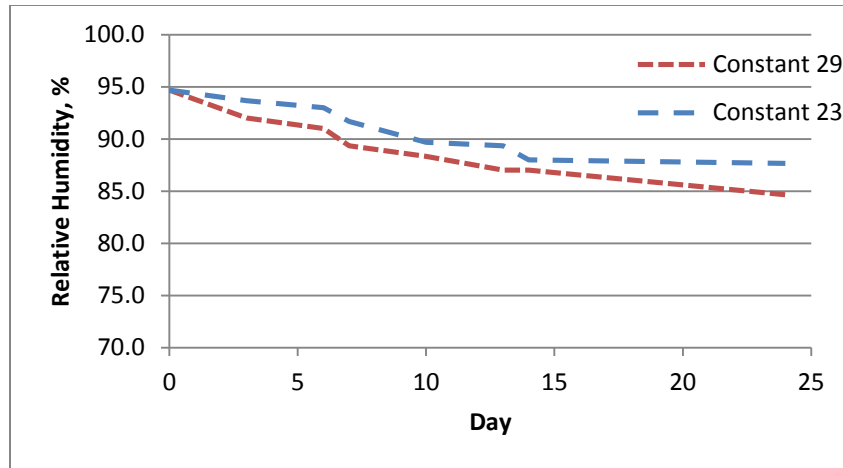


Figure 4-1c: Drying Curve for Days 0 to 24 at 60% Depth for Constant 29 and Constant 23

The 0.6% increase in RH at 40% depth in Constant 29 between Days 13 and 14 disappears at 60% depth, as the difference between the day's measurements was 0.0%. The change in RH in Constant 23 was only a 1.3% decrease between Days 6 and 7 at 60% depth, was after the samples dried 1.7% over the previous six days. Following the 1.3% drop, Constant 23 continued to dry at rate of 0.7%/day for the next six days, helping smooth the drying curve.

The flattening of the drying curve as the depth held true before Day 13 at 80% for both Constant 29 and Constant 23 (Figure 4-1d). The two drying curves had no unexpected increases and decreases in RH before Day 13.

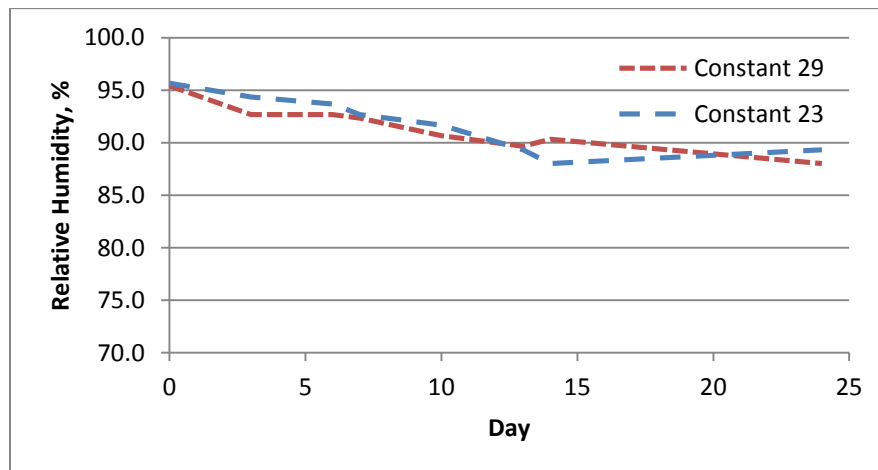


Figure 4-1d: Drying Curve for Days 0 to 24 at 80% Depth for Constant 29 and Constant 23

However, both Constant 29 and Constant 23 have unexpected increases after Day 13. Constant 29 jumped 0.6% RH between Days 13 and 14, while Constant 23 jumped 1.3% between Days 14 and 24. This was very unusual behavior since at 80% depth evaporation is not occurring and diffusion controlled the drying of concrete at this depth.

When examining the drying curves for the samples with temperature changes, the readings at 20% depth showed an increased sensitivity to the temperature change than the deeper depths. This is expected based on the trend established by Constant 29 and Constant 23, as an increased sensitivity was shown at 20% depth without any change in temperature. The drying curves for Samples 4-6, referenced as “Change 29-23-29” for Section 4.1.1, and Samples 7-9, referenced as “Change 23-29-23” for Section 4.1.1, at 20%, 40%, 60%, and 80% depths are shown in Figures 4-2a, 4-2b, 4-2c, and 4-2d. The lines at the bottom of the charts track the temperature of the samples and the value is read on the right vertical axis. The RH drying curves are shown in the top of the chart and the values are to be read from the left vertical axis.

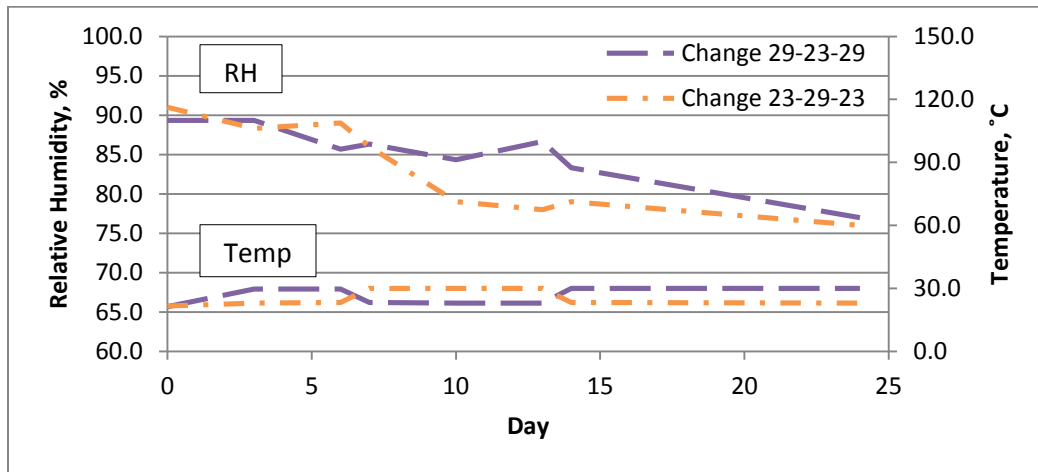


Figure 4-2a: 24 Day Drying Curves for Change 29-23-29 and Change 23-29-23 at 20% Depth

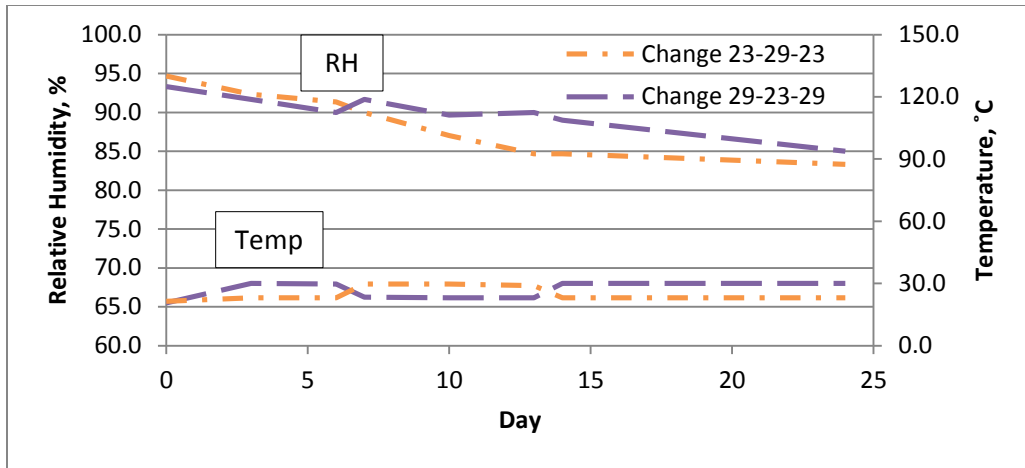


Figure 4-2b: 24 Day Drying Curves for Change 29-23-29 and Change 23-29-23 at 40% Depth

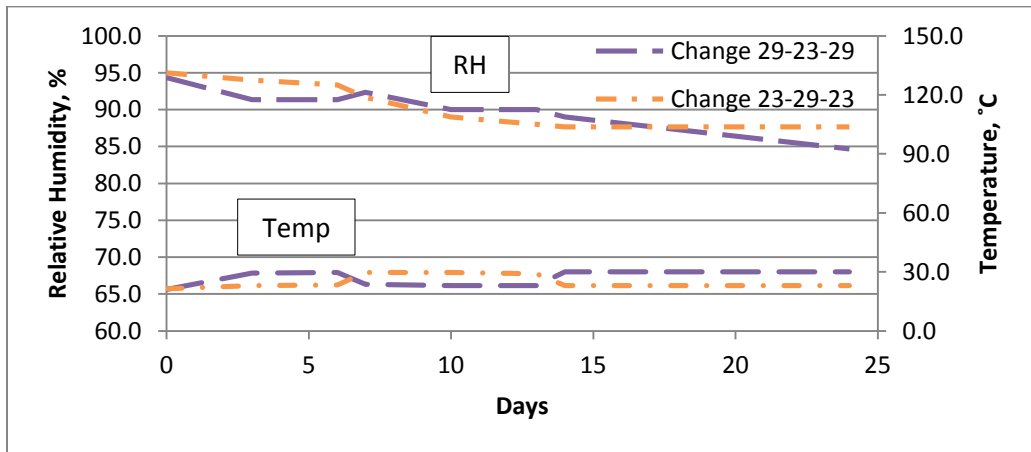


Figure 4-2c: 24 Day Drying Curves for Change 29-23-29 and Change 23-29-23 at 60% Depth

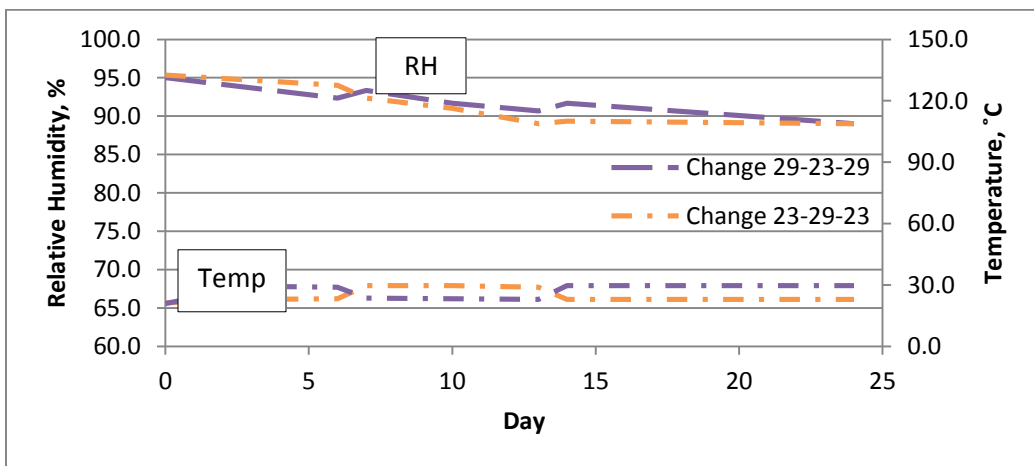


Figure 4-2d: 24 Day Drying Curves for Change 29-23-29 and Change 23-29-23 at 80% Depth

Both Change 29-23-29 and Change 23-29-23 exhibit behavior consistent with the psychrometric properties of air; when the temperature decreases, the RH increases, and when temperature increases, RH decreases. Between Days 6 and 7, Change 29-23-29 temperature decreased by 5.5°C while Change 23-29-23 temperature increased the same magnitude. The samples have another temperature change between Days 13 and 14; Change 29-23-29 temperature increased by 5.5°C, and Change 23-29-23 temperature decreased by 5.5°C.

At 20% depth, the curve fluctuates frequently, even during periods of constant temperature, but still contains noticeable changes at expected times. During the first temperature change (Day 6 to 7), Change 29-23-29 RH readings increased by a magnitude of 0.6%. Even though the magnitude was small, the jump stands out since the three days before, the samples dried at a rate of -1.33%/day and the days after the drying rate was -0.66%/day. Change 23-29-23 RH readings decreased 3.0% during the same time period, even though the 3.0% drop was larger in magnitude than the 0.6% increase in Change 29-23-29, it does not stand out as much since the days after the samples dried at a rate of -2.2%/day. The samples behaved the same during the second change in temperature (Day 13 to 14), as Change 23-29-23 RH readings increased 1.0%, while having drying rates of approximately -0.3%/day on either side of the increase. However, the RH reading decrease of 3.4% seen in Change 29-23-29 stands out, unlike Change 23-29-23, since the three days before the samples dried at a rate of +0.9%/day.

Measurements at 40% depth followed the same pattern established by Constant 29 and Constant 23; a smoothing of the curve while exhibiting much of the same behavior. There was less variation in the readings at 40% when compared to that seen at 20% depth and there were no RH spikes not associated with a change in temperature. During the first temperature change, the decrease in temperature of Change 29-23-29 caused an increase of 1.7% RH. The 1.7% jump

was accompanied by drying rates of approximately  $-0.6\%/day$  on the three days before and after. As seen at 20%, the decrease of 1.3% RH seen by Change 23-29-23 did not stand out, since afterwards the samples continued to dry at a rate of  $-0.9\%/day$  until Day 13. When Change 23-29-23 experience the second temperature change between Days 13 and 14, the expected spike in RH was missing. However, since Change 23-29-23 had been drying at a rapid rate for the six days prior, the 0.0% RH change was still reminiscent of the psychrometric properties. Similar to previous trends in RH with samples increasing temperature, the 1.0% decrease in RH seen by Change 29-23-29 during the second temperature change was not noticeable due to a similar drying period afterwards.

The established trends continued when examining the drying curve at 60% and 80% for Change 29-23-29 and Change 23-29-23. The only unexpected behavior occurred in Change 29-23-29 at 80% during the Day 13 to 14 temperature change. Between Days 13 and 14 Change 29-23-29 increased in temperature, however, the RH at 80% increased by 1.0% RH. This jump was the only unexpected jump between 40%, 60%, and 80% depths and was most likely an anomaly.

When the samples have a decrease in their temperatures, the RH measurements had a small spike, while when the temperatures increased the RH measurements decreased and continued to decrease at a similar rate. The last trend raises a question about the concrete samples: are the diffusion and evaporation parameters controlling instead of the psychrometric properties?

#### **Section 4.1.2: Examination of Sample Profiles**

Both diffusion and evaporation are controlled by humidity gradients; for diffusion it is the gradient between the bottom and top of the slab, and for evaporation it is the gradient between the concrete and the ambient air. Evaporation is also influenced by the finishing of the

surface, ambient temperature, and air movement at the surface. At the time the concrete was poured, the RH of the concrete was at 100% through the entire sample. By examining the moisture profiles of all the samples (Figure 4-3), it is clear that the evaporation rate was greater than the diffusion rate, since the measurements at 20% depth have a lower RH reading than at 80% depth.

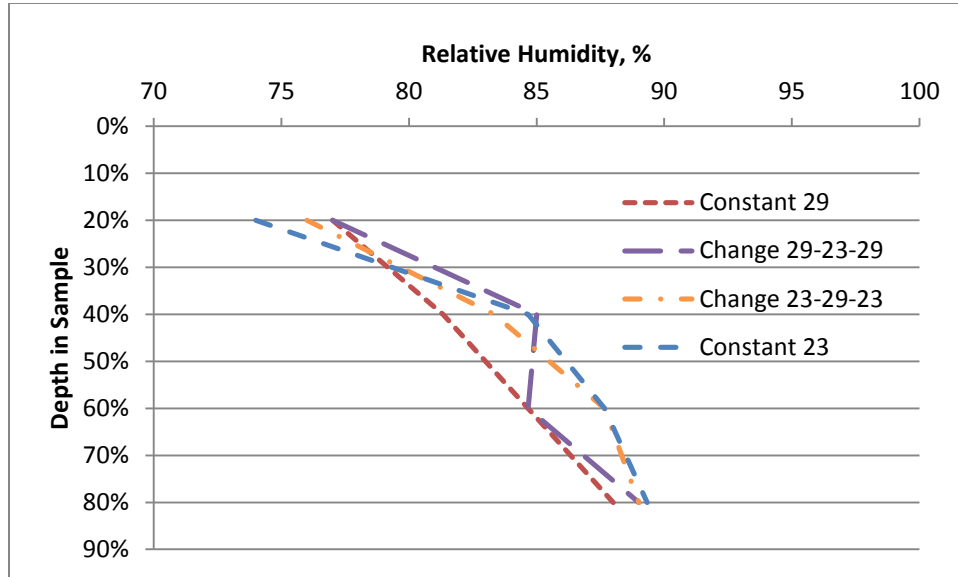


Figure 4-3: Moisture Profiles of All Samples on Day 24

If the diffusion rate was the same or greater than the evaporation rate, the moisture profiles would be uniform throughout the depth of the specimen. Since evaporation occurred at a rate greater than diffusion, the top dried quicker than the remainder of the specimen. At higher ambient temperatures, evaporation occurred at rate greater than at lower temperatures. The RH at the top of the slab is dropping quicker than the bottom, and the humidity gradient has increased, increasing the rate of diffusion. It is possible that these effects from evaporation and diffusion controlled in the 24 hour span between measurements, and would explain why the phenomenon was only present when the temperature increased, and not when temperature decreased.

The samples being drier at the surface of the concrete than the bottom was expected. However, the samples that had the lowest RH readings at 20% depth were not expected. According to the West & Holmes (2005) model, the samples exposed to greater ambient temperatures with the same ambient RH, should have lower RH measurements throughout the depth. The samples that were exposed to a constant 29.4°C, Samples 1-3, should have lower RH readings at 20% and 40%, before converging to a similar RH as the rest of the samples. At 20% depth, the samples exposed to a constant 23.9°C, Samples 10-12, have the lowest RH reading, 74% RH compared to 77% for Samples 1-3. At 40% depth Samples 1-3 were drier than the other samples, 81.3% compared to 84.7% for Samples 10-12, and at 80% depth the RH measurements were the same across all samples at approximately 89%. The behavior at depths lower than 40% were more consistent with the predictions set forth by Holmes and West (2005), and the likely divergence from the expected behavior is from the variability in the samples near the surface, a phenomenon noted in Section 4.1.1.

### **Section 4.1.3: Short Term Drying**

To reduce the effects from diffusion and evaporation, the time between the change in temperature and the recording of the data was shortened from 24 to 3 hours. The average temperature and RH measurements for each sample grouping is shown in Appendix B. These measurements were used to create drying curves at all of the recorded depths. The drying curves at 40% depth from the shortened time are shown below in Figure 4-4. During this round, Samples 1-3 and Samples 4-6 decreased temperature from 29.4°C to 23.9 °C, while Samples 7-9 and Samples 10-12 increased temperature from 29.4°C to 23.9°C. For clarity, the sample groupings will be renamed the following for Section 4.1.3: Samples 1-3 “Change 29-23-1”, Samples 4-6 “Change 29-23-2”, Samples 7-9 “Change 23-29-1”, Samples 10-12 “Change 23-29-



2”. The temperature change in the samples was not immediate. After 3 hours in new conditions, the temperatures for Change 29-23-1, Change 29-23-2, Change 23-29-1, and Change 23-29-2 were 24.0°C, 24.3°C, 28.0°C, and 27.7°C respectively. After 24 hours in the new environments, the samples reached the final temperature.

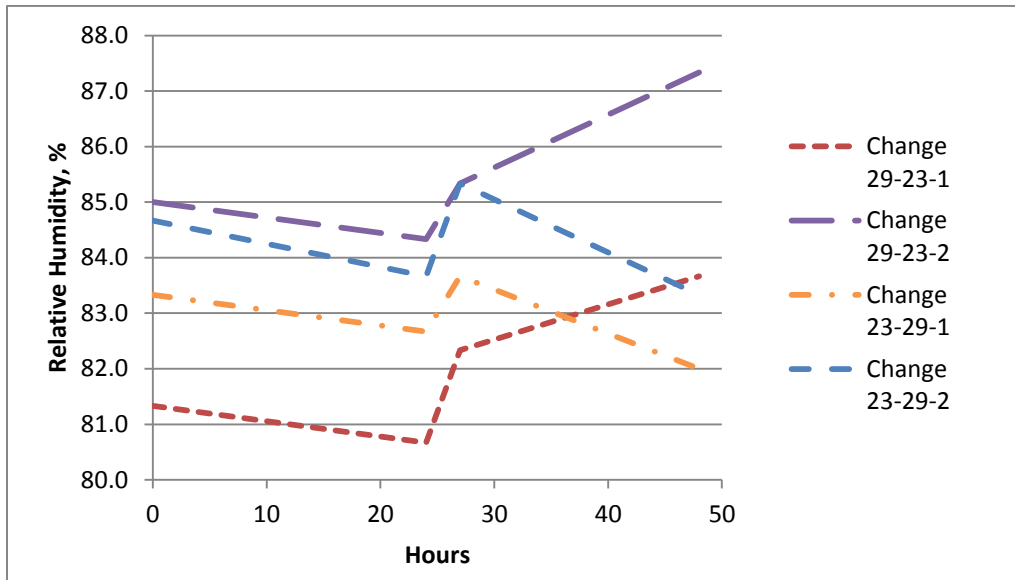


Figure 4-4: Short Term Concrete Drying Profiles at 40% Depth

All four sample groupings had a measurable increase in RH regardless of temperature change. While an increase in RH was expected if the samples environment had a drop in temperature, an upwards jump in RH coupled with an increase in temperature was not expected. Following the initial jump, Change 29-23-1 and Change 29-23-2 RH readings increased, which was concurrent with the psychrometric process since the samples continued to decrease in temperature. Change 23-29-1 and Change 23-29-2 behaved as expected, decreasing in RH in Hour 48 to values lower than the readings on Hour 24. This same behavior was found at 20%, 60%, and 80% depths, and is shown below in Figure 4-4a, Figure 4-4b, and Figure 4-4c.

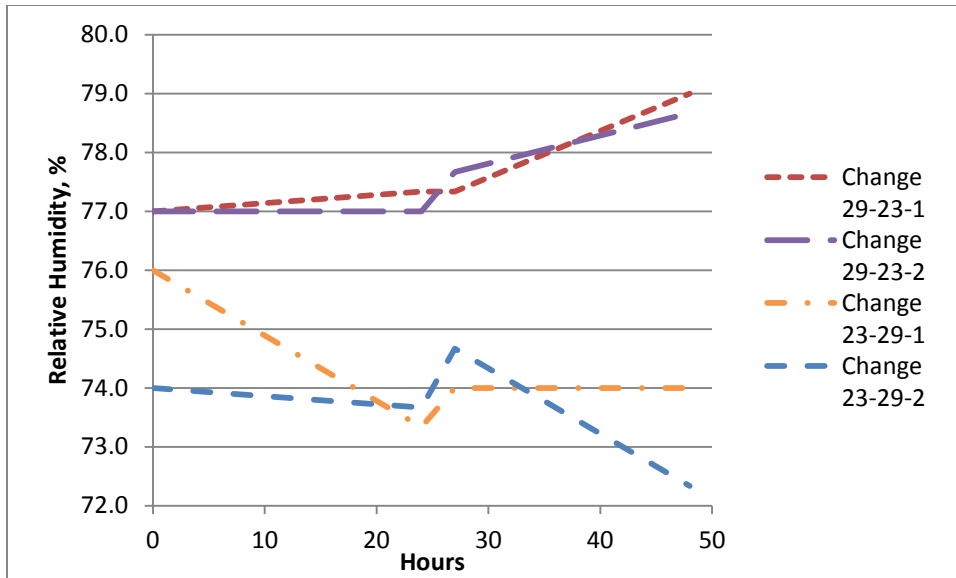


Figure 4-4a: Short Term Concrete Drying Profiles at 20% Depth

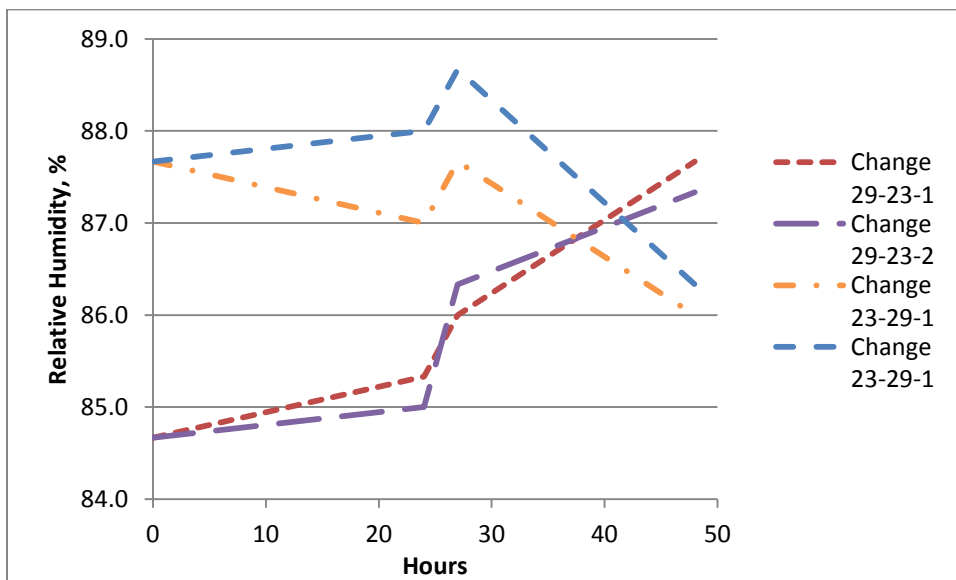


Figure 4-4b: Short Term Concrete Drying Profiles at 60% Depth

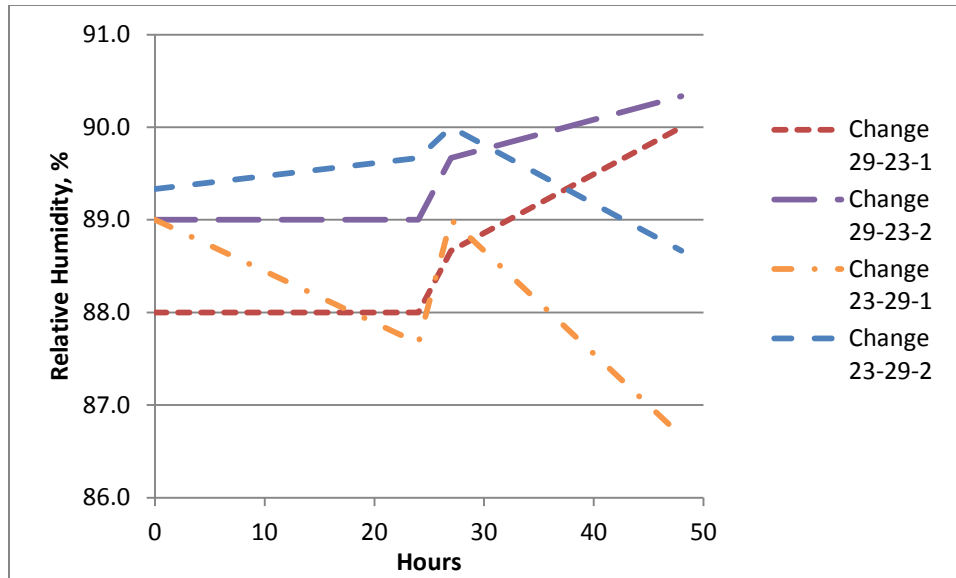


Figure 4-4c: Short Term Concrete Drying Profiles at 80% Depth

The behavior at 20%, 60%, and 80% depths was similar to 40% depth for all samples; a spike in RH was observed in all samples due to change in temperature, regardless if temperature increased or decreased. After the temperature change, RH continued to increase for samples where temperature decreased and for samples where temperature increased, RH decreased. After examining Figures 4-4a, 4-4b, and 4-4c, diffusion and evaporation appear to not control RH measurements in the short term. The behavior in Change 29-23-1 and Change 29-23-2 can be explained by the psychrometric properties of air. However, the spike seen in Change 23-29-1 and Change 23-29-2 is inconsistent with these properties. As the time after the change in temperature approaches 24 hours, the behavior in the concrete that increased in temperature becomes more influenced by evaporation and diffusion. Concrete that decreased in temperature was still controlled by psychrometric properties, since between Hours 3 and 24 the temperature was still decreasing and the RH is increasing.

#### 4.2: Examination of ambient temperature’s effect on moisture emissions

In Chapter 2, the results from the West & Holmes (2005) experiments showed that the concrete exposed to a higher temperature and larger RH gradient had a higher rate of evaporation. To test evaporation in this study, CaCl tests were conducted from Day 3 to Day 6 to track emissions of the samples, and the results are shown below in Table 4-2. The results for Samples 1, 2, and 12 have been discarded since Samples 1 and 12 were not able to obtain a proper seal and Sample 2 had some of the desiccant spill out of the dish during testing.

The ambient environments for this study had the same RH of 50% at 23.9°C and 29.4°C. On Day 3, the RH at 20% depth for Samples 1-6 was 89.8% while it was 87.8% for Samples 7-12. When the tests were completed on Day 6 the RH measurements were 86.5% and 88.4% for Samples 1-6 and Sample 7-12 respectively. The RH gradient for Samples 1-6 and Samples 7-12 on Day 3 was an average of 39.8% and 37.8% respectively. The RH gradient on Day 6 was 36.5% for Samples 1-6 and 38.4% for Samples 7-12.

Table 4-1: CaCl Results for all Samples

Sample	Start Date	Start Weight	End Date	End Weight	Moisture Content (lbs/1000sf/24hrs)	RH Day 3, 20% Depth	RH Day 6, 20% Depth
3	9-Nov	30.4	12-Nov	42.8	32.87	91	89
4	9-Nov	30.4	12-Nov	42.1	31.01	88	83
5	9-Nov	30.5	12-Nov	41.5	29.16	89	86
6	9-Nov	30.5	12-Nov	41.5	29.16	91	88
7	9-Nov	30.4	12-Nov	39.1	22.64	90	90
8	9-Nov	30.4	12-Nov	38.1	20.04	85	87
9	9-Nov	30.5	12-Nov	39.2	22.64	90	90
10	9-Nov	30.4	12-Nov	38.5	21.08	84	85
11	9-Nov	30.5	12-Nov	39.7	23.94	90	90

The average emissions for Samples 3-6 at a temperature of 29.4°C was 30.55 lbs/1000 sf/24 hours while the average emission for Samples 7-11 at 23.9°C was 22.07 lbs/1000 sf/24

hours. Even though the RH gradient for each sample grouping was approximately the same, and the RH reading at the top of each slab was similar as well, the samples in the higher temperature had greater moisture emissions. This difference in emissions happened because of the properties of air, that at higher temperatures the air can hold more water vapor than at lower temperatures, increasing the mass of water leaving the concrete.

### **4.3: Predicting RH measurements after a change in temperature**

#### **4.3.1: Predictions using the psychrometric process**

A number of patterns were found by analyzing the drying profiles of the samples in Chapter 4.1. A decrease in the temperature of a concrete sample resulted in behavior predicted by the psychrometric properties, while an increase in temperature resulted in behavior influenced by diffusion, evaporation, and psychrometrics. Table 4-2a and Table 4-2b show the measured RH of the samples at 40% depth, and compares the measured RH against the predicted RH of concrete according to psychrometric properties. A key assumption was made in the calculation; the amount of water vapor in the air in the concrete pores did not change between the measurements. For Table 4-2a, the amount of water vapor did not change between Day 6 and Day 7 and between Day 13 and Day 14, while for Table 4-2b water vapor did not change between Hour 24 and Hour 27, and between Hour 24 and Hour 48. The partial pressure of water vapor at Days 6 and 13 was used to calculate the predicted relative humidity at Days 7 and 14 respectively, and the partial pressure at Hour 24 was used to predict relative humidity at Hour 27 and Hour 48.

Table 4.2a – Psychrometric Predictions for Long Term Temperature Changes at 40% Depth

Sample		Day 6		Day 7		Day 13		Day 14	
		T, °C	RH	T, °C	RH	T, °C	RH	T, °C	RH
4-6	Measured	29.7	90%	23.3	92%	23.0	90%	30.0	89%
	Predicted	29.7	90%	23.3	131%	23.0	90%	30.0	60%
7-9	Measured	23.0	91%	29.7	90%	29.0	85%	23.0	85%
	Predicted	23.0	91%	29.7	61%	29.0	85%	23.0	121%

Table 4.2b – Psychrometric Predictions for Short Term Temperature Changes at 40% Depth

Sample		Hour 24		Hour 27		Hour 48	
		T, °C	RH	T, °C	RH	T, °C	RH
1-3	Measured	30.0	80.7%	24.0	82.3%	23.0	83.7%
	Predicted	30.0	80.7%	24.0	110.9%	23.0	117.7%
4-6	Measured	30.0	84.3%	24.7	85.3%	23.3	87.3%
	Predicted	30.0	84.3%	24.7	111.1%	23.3	120.8%
7-9	Measured	23.0	82.7%	29.7	83.7%	29.0	82.0%
	Predicted	23.0	82.7%	29.7	54.7%	29.0	58.0%
10-12	Measured	23.0	83.7%	29.7	85.3%	29.0	83.0%
	Predicted	23.0	83.7%	29.7	55.4%	29.0	58.7%

The predicted RH values determined by the psychrometric process were not similar to the measured RH values for both time periods. This was true both when the temperature increased and decreased. The key assumption, that the amount of water vapor in the air does not change, must be false. Water vapor must be entering the system between measurements. To check this assumption, a plot of dew point temperatures can be created to examine the change in water of the system.

Dew point temperature is a more consistent measurement of the water vapor content of a parcel of air than RH. Consider the key assumption from above, that there is no water vapor entering or leaving the system. The relative humidity of a parcel of air changes when temperature changes, despite the amount of water vapor being constant, since the parcel of air can hold more (or less) water vapor. Under these same conditions, the dew-point temperature of the same parcel

of air will remain constant. Equation 4-1 is the dew-point temperature as a function only of the amount of water-vapor ( $p_w$ ) in a volume of air. Since the volume of air being measured by the probes is the same every measurement and is considered an ideal gas,  $p_w$  is considered equivalent to the mass of water vapor.

$$t_d = -35.957 - 1.8726 * \ln(p_w) + 1.1689(\ln(p_w))^2 \quad [4-1]$$

Where:

$p_w$  = partial pressure of water vapor [pa]

Using the dew-point temperature measured by the Tramex Hygro-I probes during testing, a plot of Samples 1-3 and Samples 4-6 dry-bulb temperature and dew-point temperature at 40% depth are shown in Figure 4.5. The solid markers on each line represent the dry-bulb temperature, while the dashed lines represent the dew-point temperature.

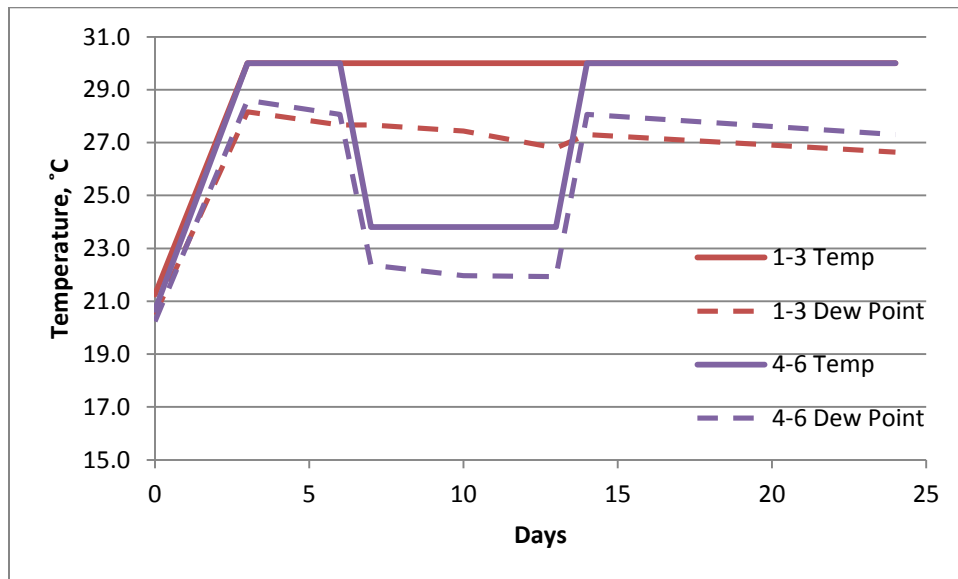


Figure 4.5: Comparison of Dry-bulb and Dew-Point Temperatures from Day 0 to Day 24

The dew-point temperatures follow the dry-bulb temperature curves closely. Since dew-point temperature is dependent on the water vapor content, the water vapor of the air content changes as the dry-bulb temperature changes. This is what causes the unpredictable RH

behavior; *the amount of moisture in the air does not remain constant*. As the ability for the air to hold moisture changes, the amount of water in the air changes to accommodate this, making the initial assumption that the amount of water vapor does not change false. This is able to happen since the free water in concrete is present in both the liquid and gaseous phases. If free water was only present in the gaseous phase, then the measured relative humidity of the concrete would follow the psychrometric properties of air. However, since free water is present the amount of water vapor in the air is able to change.

Despite not being able to predict the magnitude of RH change in concrete when temperature changes, the psychrometric properties still dictate behavior in the concrete. The small increases in RH when temperature decreases do not occur if diffusion and evaporation are controlling behaviors. As such, the changes in RH due to a change in temperature in a time frame of 24 hours or less cannot be predicted by previously developed drying models, and therefore a new model needs to be created to predict the behavior of concrete.

Is it possible to predict how much the water vapor content will change with a change in temperature, taking only into consideration the previous measurements relative humidity and temperature of the air? As discussed in Chapter 3, relative humidity is dependent on both the partial pressure of water vapor and the saturation partial pressure of water. The relationship between the saturation partial pressure of water and temperature is known, and shown in Equation 2.4. However, the ability to predict how the partial pressure of water vapor changes with a change in temperature is not known.

#### **4.3.2 Developing a model to predict RH after a change in temperature**

To accurately predict the relative humidity in concrete after a change in temperature, it is necessary to first predict how the partial pressure of water vapor will change within the pores.



There is currently no known model to predict the changes in the partial pressure of water vapor when the air is in contact with liquid water. In order to develop one, a plot was created to track the partial pressure of water vapor,  $p_w$ , with respect to the temperature at which it was recorded. Once the plot was created, a trend line was created to allow for a rough prediction of the partial pressure of water vapor. The results are shown in Figure 4-6.

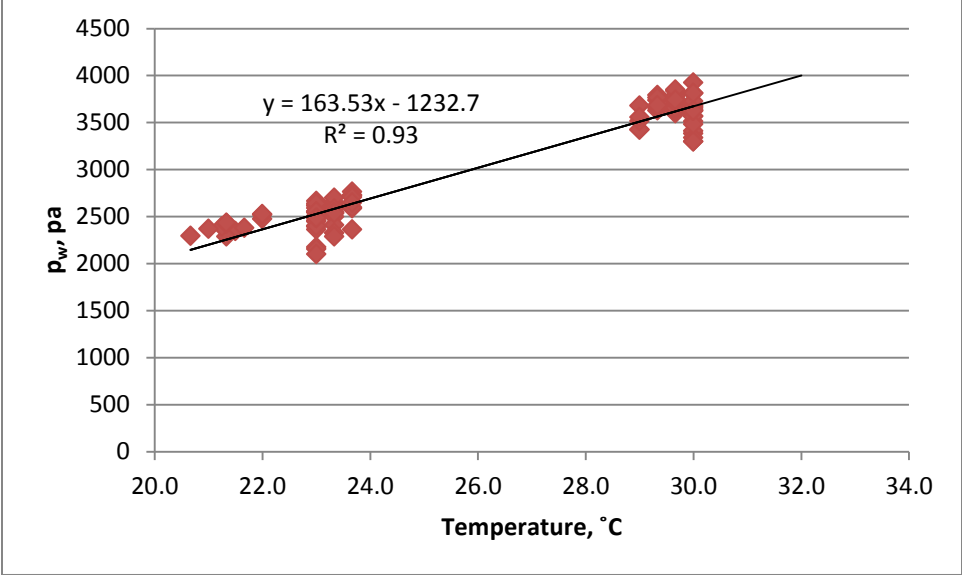


Figure 4-6: Partial Pressure of Water Vapor vs. Temperature

The computed trend line (Eq 4-2) is a predictor of what the partial pressure of water vapor will be depending on the temperature of the concrete. However, Equation 4.2 does not consider the age or dryness of the concrete, and a correction factor is needed. To see if there are any trends in RH measurements, a plot of the actual RH measurements recorded by the Hyrgo-I probe on the x-axis and the predicted RH using Equation 4-2 are shown in Figure 4-7a for samples with a decrease in temperature and in Figure 4-7b for samples with an increase in temperature.

$$p_{w\_pred} = 163.53 * T_{fin} - 1232.7 \quad [4-2]$$

Where:

$p_{w\_pred}$  = predicted partial pressure of water vapor [pa]

$T_{fin}$  = dry-bulb temperature after the temperature change [°C]

The samples shown are test samples with a change in temperature, since the model is only meant to predict RH immediately after a temperature change, not model diffusion and evaporation parameters. The different markers group the same sample together for easier identification. The numbers in the legend do not represent sample numbers; each number represents one change in temperature recorded at one depth. The line drawn on both charts represents Equation 4-2.

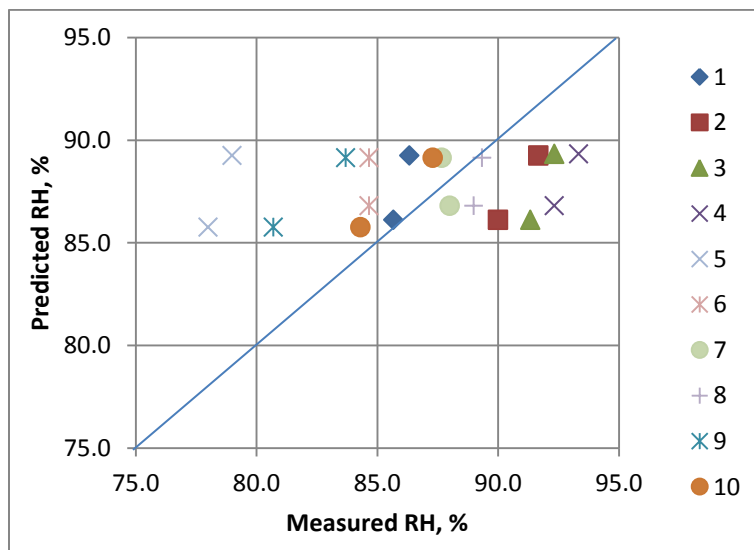


Figure 4-7a: Predicted RH value vs Measured RH for an increase in temperature

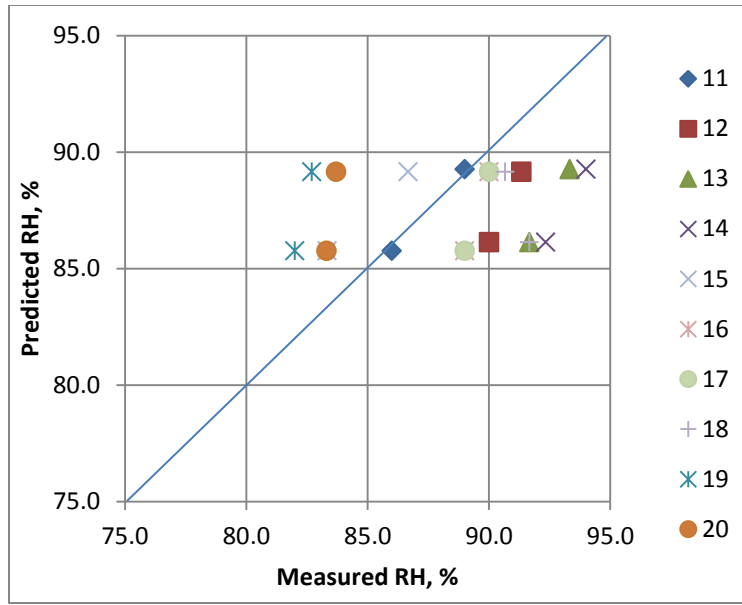


Figure 4-7b: Predicted RH Values vs Measured RH for an Increase in Temperature

For both increases and decreases in temperature, the initial and final measurements fall close to the same distance away from the blue line. This correlation shows that the initial RH of the concrete can be used in conjunction with Equation 4-2 to predict the final RH of the concrete. This will be done by taking the percent error of Equation 4-2 predicting the initial RH, and apply that difference as a correction to the predicted RH at the final temperature. The process is shown in Equation 4-3.

$$RH = RH_{pred} - \frac{RH_{ini} - RH_{meas}}{RH_{ini}} * RH_{pred} \quad [4-3]$$

Where:

- $RH_{pred}$  = RH calculated using the results of equation 4.2 and final temperature
- $RH_{ini}$  = RH calculated using the results of equation 4.2 and initial temperature
- $RH_{meas}$  = measured RH at initial temperature

Equation 4-3 was then used to develop Tables 4-3 and 4-3. Table 4-3 includes all samples that underwent a decrease in temperature, while Table 4-4 includes all samples that increased in temperature. In both tables, the results from Equation 4-3 are in the “RH” column, while the “Predicted RH” column is RH value calculated at the temperature using Equation 4-2. The

results in the RH column have been bolded, along with the Measured RH value to be compared to. The temperature and measured RH values are from the testing of the concrete samples.

Table 4-3: Predicted RH Measurements for concrete with decreases in temperature

ID Num		Temp [°C]	Measured RH [%]	Predicted RH [%]	RH [%]	% Error
1	Initial	29.7	85.7	86.1		
1	Final	23.3	<b>86.3</b>	89.3	<b>88.8</b>	2.8%
2	Initial	29.7	90.0	86.1		
2	Final	23.3	<b>91.7</b>	89.3	<b>93.1</b>	1.5%
3	Initial	29.7	91.3	86.1		
3	Final	23.7	<b>92.3</b>	89.3	<b>94.4</b>	2.2%
4	Initial	29.0	92.3	86.8		
4	Final	23.7	<b>93.3</b>	89.3	<b>94.7</b>	1.4%
5	Initial	30.0	78.0	85.8		
5	Final	23.3	<b>79.0</b>	89.3	<b>80.4</b>	1.7%
6	Initial	29.0	84.7	86.8		
6	Final	23.0	<b>84.7</b>	89.2	<b>86.9</b>	2.6%
7	Initial	29.0	88.0	86.8		
7	Final	23.0	<b>87.7</b>	89.2	<b>90.4</b>	3.0%
8	Initial	29.0	89.0	86.8		
8	Final	23.0	<b>89.3</b>	89.2	<b>91.4</b>	2.2%
9	Initial	30.0	80.7	85.8		
9	Final	23.0	<b>83.7</b>	89.2	<b>83.6</b>	0.2%
10	Initial	30.0	84.3	85.8		
10	Final	23.0	<b>87.3</b>	89.2	<b>87.6</b>	0.3%

Table 4-4: Predicted RH Measurements for concrete with increases in temperature

ID Num		Temp [°C]	Measured RH [%]	Predicted RH [%]	RH [%]	% Error
11	Initial	23.3	89.0	89.3		
11	Final	30.0	<b>86.0</b>	85.8	<b>85.5</b>	0.6%
12	Initial	23.0	91.3	89.2		
12	Final	29.7	<b>90.0</b>	86.1	<b>88.2</b>	2.1%
13	Initial	23.3	93.3	89.3		
13	Final	29.7	<b>91.7</b>	86.1	<b>89.9</b>	2.0%
14	Initial	23.3	94.0	89.3		
14	Final	29.7	<b>92.3</b>	86.1	<b>90.5</b>	2.1%
15	Initial	23.0	86.7	89.2		
15	Final	30.0	<b>83.3</b>	85.8	<b>83.3</b>	0.0%
16	Initial	23.0	90.0	89.2		
16	Final	30.0	<b>89.0</b>	85.8	<b>86.6</b>	2.8%
17	Initial	23.0	90.0	89.2		
17	Final	30.0	<b>89.0</b>	85.8	<b>86.6</b>	2.8%
18	Initial	23.0	90.7	89.2		
18	Final	29.7	<b>91.7</b>	86.1	<b>87.6</b>	4.7%
19	Initial	23.0	82.7	89.2		
19	Final	30.0	<b>82.0</b>	85.8	<b>79.1</b>	3.7%
20	Initial	23.0	83.7	89.2		
20	Final	30.0	<b>83.3</b>	85.8	<b>80.2</b>	3.9%

In both situations, the temperature increasing and the temperature decreasing, the combination of Equations 4-2 and 4-3 are able to predict how much the RH of the concrete will change. The equations predicted RH better for a decrease in temperature, than an increase. This happens because Equation 4.2 often over-predicts how much the RH will decrease. The average over-prediction is usually by about 2%, and since it is so consistent a new equation similar to Equation 4.2 could be developed to predict RH when temperature decreases only. However, the sample size is small, and the new equation would not provide much overall improvement. The range of percent error for the predictions is between 0.2% and 3.9%, which is reasonable for predicting behavior in a material that is inconsistent.

## Chapter 5: Summary

### 5.1 Conclusions

When examining the RH of concrete after a change in ambient temperature, the expected behavior according to psychrometric properties is that the concrete RH decreases with an increase in temperature, while RH increases with a decrease in temperature. In this study, the typical change in RH of the samples was around 2% to 4%, regardless of whether the ambient temperature increased or decreased. The samples had their largest changes in RH at 20% depth, but the changes in RH at 40%, 60%, and 80% depths was still significant. However, large spikes and drops at 20% depth should not be considered too heavily since samples that remained at constant temperature also had changes in RH at the same magnitude. The remaining depths, 40%, 60%, and 80%, all had smooth drying curves in the constant temperature samples, and changes in RH after a change of temperature represent a sensitivity.

The samples were measured at two different intervals after a change in temperature; 3 hours and 24 hours. The psychrometric process was then used to predict the change in RH after the change in temperature. The measured difference in RH after the change in temperature was typically 2% - 4%, while the psychrometric process predicted the change in RH to be between 20% - 40%. This order of magnitude difference between the measured RH and predicted RH was due to one bad assumption; that the amount of water vapor in the pores remains constant between measurements.

After concrete has hardened, free water exists in concrete in two forms, liquid water and water vapor. As temperature increases, the ability for the air in the concrete pores to hold more water vapor also increases. As the temperature increases, the amount of water vapor in the air does not remain constant; the existing pressure in the pores forces more of the water in the liquid

stage into the gaseous state. The air reaches equilibrium at approximately the same RH as before the temperature, slightly higher when the ambient temperature increases, slightly lower when the ambient temperature decreases. Even though the change in water vapor cannot be predicted by psychrometric properties, or concrete drying models, trends in the data can be used to predict the RH in concrete after a change in temperature.

By developing a relationship between partial pressure of water vapor and temperature, and accounting for the RH at the previous temperature, a model was created to predict the change in RH immediately following a change of temperature. The model was able to predict the new RH measurements within 5% error, much closer than the psychrometric process. More data at the temperatures used in the study and other temperatures is still needed so the model can be properly calibrated.

Overall, measuring the RH of concrete is very robust to minor changes in temperature. A 5.5°C (10°F) change in temperature rarely changed the RH outside the  $\pm 2\%$  RH accuracy of the probes. This is in contrast to MVER tests, which are very sensitive to changes in temperature. In concrete samples that measured within 1% RH at 20% depth, the results at 29.4°C vs 23.9°C were 33% greater.

## 5.2 Limitations of Study

There are several limitations for this study that are outlined below:

- Only two environmental chambers were available for the study, limiting the possible temperature conditions.
- The weight of the samples and space within the environmental chambers prevented more samples from being tested at the same time.
- Even though the probes are the most precise RH probes available, the  $\pm 2\%$  accuracy limits the conclusions that can be made.
- All samples could not be mixed at the same time, and even though a consistent batch was used for each mix there is no way to ensure uniformity across the samples.
- A finite element analysis of the two drying conditions was not run to compare against the experimental data.
- Only one  $w/c$  ratio was tested, additional tests examining the behavior of other ratios should be conducted
- Even though the containers were sealed, it is impossible to perfectly seal the seam between the form and the concrete to ensure only one-sided drying conditions



### **5.3 Future Work**

For future study, tests at additional temperatures above and below 23.9°C and 29.4°C are recommended. The results from the tests can be used to expand the temperature change model developed, or can show that RH measurements are stable despite any magnitude change in ambient temperature. MVER tests should also be conducted at the different temperatures and after temperature changes to gain a better understanding of how temperature can affect concrete emission tests. The results of the MVER test should be compared to the results of the RH measurements to develop a correlation between the two testing methods.

A finite element analysis using the established diffusion and evaporation models should be conducted at cyclic temperatures. The results can be compared to the drying profiles to determine if behavior is in-line with the diffusion and evaporation models, or due to different variables.

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## Appendix

### Appendix A: Long Term Drying Data (Sample Grouping Averages)

1 – 20% Depth

<b>20 % Depth</b>	<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Day 0</b> T, °C	21.5	21.3	21.7	22.0
RH, %	90.6	89.3	91.0	92.7
Td, °C	20.3	19.8	20.8	21.2
<b>Day 3</b> T, °C	30.0	29.7	23.0	23.7
RH, %	89.0	89.3	88.3	87.7
Td, °C	27.9	27.9	21.8	21.7
<b>Day 6</b> T, °C	29.3	29.7	23.3	23.3
RH, %	88.0	85.7	89.0	87.7
Td, °C	27.7	27.3	21.7	21.6
<b>Day 7</b> T, °C	29.7	23.3	30.0	23.3
RH, %	86.3	86.3	86.0	83.3
Td, °C	27.5	21.8	27.7	20.9
<b>Day 10</b> T, °C	30.0	23.0	30.0	23.3
RH, %	83.3	84.3	79.0	80.3
Td, °C	26.4	20.9	25.9	20.3
<b>Day 13</b> T, °C	30.0	23.0	30.0	23.7
RH, %	79.7	86.7	78.0	80.0
Td, °C	26.3	21.4	25.7	19.8
<b>Day 14</b> T, °C	30.0	30.0	23.3	23.0
RH, %	82.0	83.3	79.0	76.7
Td, °C	26.7	26.8	20.0	19.1
<b>Day 24</b> T, °C	30.0	30.0	23.0	23.0
RH, %	77.0	77.0	76.0	74.0
Td, °C	26.0	25.9	19.4	18.7

2 – 40% Depth

<b>40% Depth</b>	<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Day 0</b> T, °C	21.3	20.7	21.3	22.0
RH, %	93.9	93.3	94.7	94.3
Td, °C	20.5	20.2	20.7	21.1
<b>Day 3</b> T, °C	29.3	30.0	23.0	23.7
RH, %	90.7	91.7	92.3	92.3
Td, °C	28.2	28.6	22.3	22.7
<b>Day 6</b> T, °C	29.3	29.7	23.0	23.0
RH, %	88.7	90.0	91.3	92.3
Td, °C	27.7	28.1	22.2	22.4
<b>Day 7</b> T, °C	29.7	23.3	29.7	23.3
RH, %	88.0	91.7	90.0	90.3
Td, °C	27.7	22.4	28.2	22.2
<b>Day 10</b> T, °C	30.0	23.0	29.7	23.3
RH, %	85.7	89.7	87.0	89.3
Td, °C	27.4	22.0	27.0	22.0
<b>Day 13</b> T, °C	29.0	23.0	29.0	23.7
RH, %	84.7	90.0	84.7	88.0
Td, °C	26.8	21.9	27.0	21.8
<b>Day 14</b> T, °C	30.0	30.0	23.0	23.0
RH, %	85.3	89.0	84.7	86.3
Td, °C	27.3	28.1	21.1	21.3
<b>Day 24</b> T, °C	30	30	23	23
RH, %	81.3	85.0	83.3	84.7
Td, °C	26.6	27.3	20.7	21.1

3 – 60% Depth

<b>60% Depth</b>	<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Day 0</b> T, °C	21.3	21.0	21.3	22.0
RH, %	94.7	94.3	95.0	94.7
Td, °C	20.6	20.3	20.8	21.1
<b>Day 3</b> T, °C	29.3	29.3	23.0	23.7
RH, %	92.0	91.3	94.0	93.7
Td, °C	28.3	28.4	22.7	22.8
<b>Day 6</b> T, °C	29.0	29.7	23.3	23.0
RH, %	91.0	91.3	93.3	93.0
Td, °C	28.0	28.1	22.6	22.6
<b>Day 7</b> T, °C	29.3	23.7	29.7	23.7
RH, %	89.3	92.3	91.7	91.7
Td, °C	27.7	22.6	28.5	22.5
<b>Day 10</b> T, °C	29.7	23.0	29.7	23.7
RH, %	88.3	90.0	89.0	89.7
Td, °C	27.8	22.0	28.0	22.1
<b>Day 13</b> T, °C	29.0	23.0	29.0	23.3
RH, %	87.0	90.0	88.0	89.3
Td, °C	27.1	21.9	27.4	22.1
<b>Day 14</b> T, °C	30.0	30.0	23.0	23.3
RH, %	87.0	89.0	87.7	88.0
Td, °C	27.6	28.0	21.6	21.7
<b>Day 24</b> T, °C	30.0	30.0	23.0	23.3
RH, %	84.7	84.7	87.7	87.7
Td, °C	27.3	26.9	21.5	21.8

4 – 80% Depth

<b>80%</b>		<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Day 0</b>	T, °C	21.3	21.0	21.3	21.7
	RH, %	95.4	95.0	95.3	95.7
	Td, °C	20.5	20.4	20.6	20.7
<b>Day 3</b>	T, °C	29.0	29.3	23.0	23.7
	RH, %	92.7	93.7	94.7	94.3
	Td, °C	28.3	28.7	22.8	22.9
<b>Day 6</b>	T, °C	29.0	29.0	23.3	23.0
	RH, %	92.7	92.3	94.0	93.7
	Td, °C	28.2	28.3	22.8	22.8
<b>Day 7</b>	T, °C	29.0	23.7	29.7	23.3
	RH, %	92.3	93.3	92.3	92.7
	Td, °C	28.2	22.9	28.5	22.7
<b>Day 10</b>	T, °C	29.3	23.3	29.7	23.7
	RH, %	90.7	91.7	91.0	91.7
	Td, °C	28.1	22.4	28.2	22.5
<b>Day 13</b>	T, °C	29.0	23.0	29.0	23.7
	RH, %	89.7	90.7	89.0	89.3
	Td, °C	27.4	22.1	27.5	22.1
<b>Day 14</b>	T, °C	29.3	29.7	23.0	23.0
	RH, %	90.3	91.7	89.3	88.0
	Td, °C	28.2	28.3	22.0	21.7
<b>Day 24</b>	T, °C	30.0	29.7	23.0	23.0
	RH, %	88.0	89.0	89.0	89.3
	Td, °C	27.9	27.9	21.8	21.9

## Appendix B: Short Term Drying Data (Sample Grouping Averages)

### 1 – 20% Depth

<b>20 % Depth</b>		<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Hour 0</b>	T, °C	30.0	30.0	23.0	23.0
	RH, %	77.0	77.0	76.0	74.0
	Td, °C	26.0	25.9	19.4	18.7
<b>Hour 24</b>	T, °C	30.0	29.7	23.0	23.3
	RH, %	77.3	77.0	73.3	73.7
	Td, °C	25.5	25.6	18.6	18.8
<b>Hour 27</b>	T, °C	24.0	24.3	28.0	27.7
	RH, %	77.3	77.7	74.0	74.7
	Td, °C	20.2	20.6	23.2	23.4
<b>Hour 48</b>	T, °C	23.0	23.7	30.0	30.0
	RH, %	79.0	78.7	74.0	72.3
	Td, °C	19.4	20.0	25.0	24.7

### 2 – 40% Depth

<b>40% Depth</b>		<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Hour 0</b>	T, °C	30.0	30.0	23.0	23.0
	RH, %	81.3	85.0	83.3	84.7
	Td, °C	26.6	27.3	20.7	21.1
<b>Hour 24</b>	T, °C	30.0	30.0	23.0	23.7
	RH, %	80.7	84.3	82.7	83.7
	Td, °C	26.4	27.2	20.2	21.1
<b>Hour 27</b>	T, °C	24.0	24.7	28.0	28.3
	RH, %	82.3	85.3	83.7	85.3
	Td, °C	21.1	22.3	25.3	25.8
<b>Hour 48</b>	T, °C	23.0	23.3	30.0	30.0
	RH, %	83.7	87.3	82.0	83.3
	Td, °C	20.7	21.7	26.9	26.9



3 – 60% Depth

<b>60% Depth</b>		<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Hour 0</b>	T, °C	30.0	30.0	23.0	23.3
	RH, %	84.7	84.7	87.7	87.7
	Td, °C	27.3	26.9	21.5	21.8
<b>Hour 24</b>	T, °C	30.0	29.7	23.0	23.0
	RH, %	85.3	85.0	87.0	88.0
	Td, °C	27.2	26.7	21.4	21.7
<b>Hour 27</b>	T, °C	24.0	24.0	28.0	28.7
	RH, %	86.0	86.3	87.7	88.7
	Td, °C	21.4	22.2	26.2	26.8
<b>Hour 48</b>	T, °C	23.0	23.3	30.0	30.0
	RH, %	87.7	87.3	86.0	86.3
	Td, °C	21.4	21.7	27.0	27.6

4 – 80% Depth

<b>80% Depth</b>		<b>1-3</b>	<b>4-6</b>	<b>7-9</b>	<b>10-12</b>
<b>Hour 0</b>	T, °C	30.0	29.7	23.0	23.0
	RH, %	88.0	89.0	89.0	89.3
	Td, °C	27.9	27.9	21.8	21.9
<b>Hour 24</b>	T, °C	29.0	29.7	23.0	23.0
	RH, %	88.0	89.0	87.7	89.7
	Td, °C	27.5	27.8	21.6	21.8
<b>Hour 27</b>	T, °C	24.0	24.0	28.0	28.7
	RH, %	88.7	89.7	89.0	90.0
	Td, °C	22.3	22.7	26.5	27.1
<b>Hour 48</b>	T, °C	23.0	23.3	29.3	29.7
	RH, %	90.0	90.3	86.7	88.7
	Td, °C	21.9	22.2	27.4	27.8