MEASURING RELATIVE HUMIDITY IN CONCRETE PAVEMENTS AS A METHOD TO ASSESS ASR MITIGATION MEASURES

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Abstract

Alkali-silica reaction (ASR) in concrete is partly facilitated by available moisture within the concrete. In order to better understand this facilitation and to develop processes for ASR mitigation methods, it is necessary to establish a means of monitoring internal relative humidity (RH) within the concrete. Current procedures for measuring RH are time consuming; requiring several hours of equilibration time and specific external conditions to yield accurate results. In order to better understand RH monitoring, laboratory tests were conducted using commercially available RH probes and different controlled environments. Probes were carefully monitored and calibrated in controlled environments, and laboratory tests on internal RH were conducted on concrete slabs in ambient conditions as well as concrete prisms in controlled environments. Preliminary results show that differing probes must be calibrated at different intervals and require different equilibrium times. Current internal RH test procedures are inefficient in terms of equilibration and measurement parameters.

KEYWORDS: Alkali-silica reaction (ASR), relative humidity, pavements, mitigation

1 INTRODUCTION

Mitigating alkali-silica reaction in concrete is achieved through reducing the available moisture within the concrete. One method of validating mitigation measures is through monitoring the internal relative humidity (RH) of the concrete. Measuring relative humidity in the field is difficult due to fluctuation in temperature. Several hours are required for temperature and humidity equilibrium between the humidity probe and the concrete. In addition, the temperature of the concrete needs to be between 21 and 24 degrees Celsius [1]. Changes in temperature during monitoring increase the time required for equilibrium. Several methods have been developed for measuring RH in the field. Portable digital RH probes that use capacitive or resistive type sensors are often used because of the rapid and repeatable results [2]. The process of measuring RH involves drilling a port to the selected depth within the concrete and then cleaning the port and inserting a plastic tube, which is then affixed with epoxy and plugged with rubber. After the air in the port reaches temperature and RH equilibrium with the concrete, the plug is removed and a probe is inserted [3, 4]. The probe remains in the port until it is in equilibrium with the air in the port.

This method has proven effective in several publications [3, 5, 6]. However, there are some limitations to this method, which can be difficult to overcome. The measurements must be conducted when the temperature of the concrete is near 21 to 24 degrees Celsius and the temperature is stable. If the temperature fluctuates rapidly during measurements the probe will require additional time to equilibrate, and may not provide accurate measurements. In addition, fluctuations in temperature can cause moisture to condense within the port, which will cause RH readings that are artificially high [3, 7].

Improved methods for measuring RH in the field are being evaluated as part of a larger ongoing research program between the University of Arkansas and the Arkansas State Highway and Transportation Department (AHTD). The evaluation of RH was conducted in three phases, the first phase included calibration of RH probes. The second phase, was to determine the required equilibrium time for measuring RH in concrete elements and the third phase evaluated the critical RH required to sustain ASR related expansion over a range of temperatures.

2 MATERIALS AND METHODS

2.1 Calibration

Two different probes were used to measure relative humidity: Vaisala HMP40S and Labjack EI1050 probes. The Vaisala probes use a sensor that is accurate within 1.5 percent below a relative

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humidity of 90 percent, and within 2.5 percent at a relative humidity above 90 percent. The Labjack probes are within 3.5 percent accuracy at all relative humidity levels. Both probes function best in a temperature range of 0 to 40 degrees Celsius. Three Vaisala probes were available at the start of the project; however, one of the probes malfunctioned during the project. In addition, eighteen Labjack probes were used during the project, with three malfunctioning. The probe malfunctions were all caused by ammonium sulfate saturated salt solution, which reacted with the soldered connections in the probes and resulted in failure of the RH sensor.

In order to check the accuracy and compare the two types of probes, the probes needed to be tested in known relative humidity. Three tests containers were established using saturated salt solutions. In each container a salt was added to a small amount of warm water until completely saturated, then the containers were sealed and small ports were drilled in the lid so the probes could later be placed in them. The three salts used were sodium nitrite, potassium chloride, and potassium nitrate. These salts created an approximate relative humidity of 65 percent, 85 percent, and 95 percent, respectively. The containers were placed in an environmental chamber at a constant temperature of 23 degrees Celsius.

First a Vaisala probe was placed in each container and monitored an hour a day for three days. These measurements showed the average temperature and relative humidity readings for each Vaisala probe in each salt. Following the Vaisala specific recordings, a Vaisala probe was left in each container. Each of the 15 functioning Labjack probes was placed in each of the containers and was monitored alongside the Vaisala probe for an hour after placement, and an hour the following day. Using the average values for all these readings, differences between the probe types were documented.

2.2 Internal Relative Humidity

To begin the internal relative humidity tests, two concrete slabs were cast. Concrete slab specimens were cast using a standard *Concrete Prism Test* (CPT) mix design. The cement content was 420 kg/m^3 and the water to cement ratio was 0.45. The aggregates consisted of 1062 kg/m^3 of a non-reactive crushed limestone and 687 kg/m^3 of a moderately reactive natural sand. The slabs were placed outdoors in a moderately shady area. In order to conduct the necessary tests, six ports had to be drilled at three different depths. Each port was used for a humidity probe. A pattern was made out of cardboard with two rows of three ports evenly spaced. The pattern was placed on a slab and two ports were drilled to a depth 25 mm, 50 mm and 75 mm using a hammer drill. Once the ports were drilled, they were thoroughly cleaned to be free of dust or debris. One Vaisala probe and one Labjack probe was placed at each depth. The Labjack probes were then attached to a data acquisition board and accompanying computer and all of the probes were monitored for three days, approximately one hour a day. This process was repeated twice on each of the two slabs. Each time the manner in which the probes were placed in the concrete was changed. The first rotation, the probes were inserted using only O-rings to seal them in the concrete on the first slab, and on the second slab O rings were used for the Labjack probes and sealant was used for the Vaisala probes. On the second rotation a silicon sealant was used for all six probes per slab.

After the first tests were conducted, two of the 50mm and 75mm Vaisala ports on each slab were plugged using rubber plugs supplied by Vaisala. For each of these two depths on both slabs a new port of equal depth was drilled. Immediately after drilling and cleaning, a probe was inserted and both it and an accompanying probe in the previously drilled port was monitored for 2 to 3 hours, and monitored again the next day using the Vaisala probes. This process was used to compare the difference in RH for probes inserted into a freshly drilled port, as compared to a port which has had several days to equilibrate with the concrete.

2.3 Critical Relative Humidity and Temperature

The test method for determining the critical RH, below which ASR does not occur, involved storing ASR reactive concrete prisms at a range of temperatures and ambient relative humidity. The concrete prisms were cast following the ASTM C1293 mixture design. A highly reactive sand from El Paso, TX (Jobe) was selected as the reactive fine aggregate, because it reacts quickly. A non-reactive limestone was selected as an inert coarse aggregate. A high alkali (0.90 percent Na_2O_e) cement was used, and the alkalis were boosted to 1.25 percent by addition of NaOH pellets. The prisms were cured at 23 degrees Celsius for four weeks before being placed in the storage containers.

Standard 19 L pails were used for storage, and each container had saturated salt solution in the bottom to regulate RH within the container. Saturated salt solutions were prepared by first boiling distilled water, and then mixing in the selected salt. The concentration of salt added to the mixture was determined from the solubility of the salt at the final storage temperature. Additional salt was added to the mixture after, the mixture returned to room temperature to ensure that the solution remained saturated. Each pail was filled to a depth of 25 mm with salt solution, and then the prisms were placed within the container, so that the prisms did not come into contact with the salt solution.

The pails were then placed in a temperature regulated water bath. The temperatures and RH conditions, as well as the salts, are summarized in Table 2. Each pail contained three prisms, and the expansion values were determined as the average of three samples. The pails were removed from the temperature regulated baths and placed in an environmental chamber at 23 degrees Celsius 24 hours before measurements. Length change measurements were conducted using a standard length comparator as used for CPT testing. There were twelve temperature/RH points evaluated in the test matrix, which allowed the critical RH to be determine at three temperatures. The test matrix is summarized in Table 1, and includes the salts used to regulate RH within each container.

3 RESULTS AND DISCUSSION

3.1 Calibration

Two different types of relative humidity probes were used for data collection in the internal relative humidity measurements: Vaisala and Labjack. The Labjack probes are less expensive than the Vaisala probes and are more functional as several of them can be monitored in real time and recorded on a computer. Because of the differing probes types, a calibration factor could be used to convert between the two to eliminate measurement error due to probe performance. In order to establish these calibrations factors, each of the Labjack probes was cycled through sealed containers with different saturated salt solutions. During this, Labjack and Vaisala readings were taken simultaneously during the first hour of placement and after 24 hours.

The data collected during the first hour showed differences in equilibration times for the probes types. The 24-hour data showed that the Labjack and Vaisala probes read within a few percent relative humidity of the other probe type on most occasions and was used for the calibration table. Table 2 summarizes the difference in the average 24 hour readings using Vaisala probes as controls. The majority of Labjack probes used were within ± 3.5 percent of the control, the acceptable range per the sensor specifications. Labjack probes 6, 7, 10, and 11 all exhibited differences of more than the allowable limit, specifically in 70 percent relative humidity container. Large differences in the readings indicated some sort of probe error. The aforementioned four probes all read high in the one solution containing the relative humidity most within optimum operating range of the Vaisala probes, below 90 percent relative humidity. They could not exhibit this same large error at higher humidity levels due to the nearing maximum measurable values. This suggests that these probes are highly uncalibrated and are likely recording inaccurate data.

During the course of testing one of the Vaisala probes began malfunctioning and eventually failed to read. Due to the failure of the Vaisala probe, data points were lost or inaccurate throughout the calibration and internal relative humidity testing. Three new Labjack probes, which were to be used for the internal relative humidity tests, showed increasing disparity between relative humidity readings with the Vaisala probes over time in the calibration records. This decrease in accuracy shows that the Labjack probes accuracy may decrease faster than the Vaisala probes over time. The sensor in the Vaisala probes is more heavily protected than the sensor in the Labjack probes. Whereas the Labjack sensor is exposed and this exposure could lead to gradual loss of accuracy over time. However, the protection of the Vaisala sensor resulted in longer calibrations times than the Labjack probes under the same conditions.

3.2 Internal Relative Humidity

To observe the behavior of the relative humidity internally, two specific tests were conducted on two separate concrete slabs. Two slabs were cast for these tests and placed outside in exposed conditions. The first test was designed to observe the collection of relative humidly data at different depths. Two ports were drilled at each of three depths; 25, 50, and 75 mm. At each depth, both a Labjack and Vaisala probe was placed and monitored for three days. This was done twice for each slab. Following the six probe measurements, the ports drilled for the Vaisala probes were plugged until the second test was run. To observe the effects of time after drilling, a new port was drilled at 50 and 75 mm on each slab. Relative humidity of the new port and of an old port of equal depth was monitored for two days to observe the effect of time after drilling on the required equilibration time.

In the first rotation, results were consistent with expectations. The deeper within the concrete the probe was placed, the higher the measured relative humidity and the lower fluctuations in temperature. Over the four tests, two rotations for two slabs, one of the Vaisala probes began malfunctioning. The 25mm depth was already showing inconsistent data as seen in Figure 4, so it was deemed most useful to use the remaining two Vaisala probes at the 50 and 75mm tests. At each rotation, a different method of securing the probes in the slab was used. Figure 3 summarized when the probes were only placed with O-rings to maintain a seal between the concrete and probe casing, Figure 5 summarizes when a silicon sealant was used for the Vaisala probes only, and Figures 4 and 6 represent when all probes were sealed with silicon. For all four, the data recorded shows that the probe types converge on approximately the same relative humidity readings within the first hour or two of placement and become consistent following the first day. The rotation where no silicon sealant was used shows the highest consistency of the rotations, maintaining almost identical readings for the second and third day. For all of the rotations, the Labjack probes equilibrated faster than the Vaisala probes and remained more consistent over the following days. It appears as though the main effect of using a silicon sealant was to reduce inconsistencies between the relative humidity at different depths. This shows that exposure to ambient relative humidity, or the use of sealant has an effect on recorded relative humidity. This also suggests that even though the data was consistent with expectations it may be easier to observe differences in internal relative humidity using greater variations in depth.

The second test indicates that time after drilling has little effect on the relative humidity at depth within the concrete. The old ports and new ports were both sealed around the casing, and the old ports were plugged during the time between drilling and the beginning of readings. In Figures 1 and 2 the relative humidity of both ports is nearly identical after 24 hours and the age has little bearing there. More significantly, Figure 2 shows that the new port and old port are at the same relative humidity, within probe accuracy, as compared to one another within 3 hours after drilling. It is suggested in the literature that freshly drilled ports would give inaccurate readings and that it took three days for humidity to equilibrate before yielding accurate relative humidity readings [8]. However, from this test, it appears as though the age of the port has little effect on relative humidity and the more important factor is probe-specific equilibration time.

3.3 Critical Relative Humidity and Temperature

Concrete prism samples were stored in sealed 19 L pails, which were stored at a controlled temperature and RH. The relative humidity within each pail was controlled using saturated salt solutions. The four salts selected for controlling RH are summarized in Table 1. The actual RH for each salt solutions varies with temperature as compared to the values provided within the table. However, the temperature dependence of each salt is within ± 2.5 percent for the salts, when at a temperature between 20 and 40 degrees Celsius [9, 10].

The concrete prisms were cast with a highly reactive Jobe fine aggregate and a non-reactive limestone coarse aggregate. Due to the reactivity of this aggregate, the critical RH is actually lower than 80 percent, and from Figure 7 falls near 60 percent. Interestingly, the critical RH is similar at all three temperatures. However, this critical RH is not representative of less reactive aggregates. Therefore, the test method will be repeated with a mildly reactive fine aggregate from Arkansas. The results of this test will be used to improve field methods for measuring RH. Currently, field testing requires that RH be measured when the ambient temperature is near 21 to 24 degrees Celsius [1]. This limitation leads to two issues when measuring RH in the field. First, the weather must be appropriate so that the internal concrete temperature falls within or near this small range. Second, and more difficult to achieve, the temperature must remain within this range for a sufficient period in order for the RH probe to achieve temperature and humidity equilibrium with the concrete. However, the temperature of the concrete often changes faster than that of the probe introducing additional errors. Therefore, knowing the critical RH over a broad range of temperatures allows field measurements to be conducted at a wider range of temperatures. However, this does not address the second limitation, and RH must still be measured when concrete temperature is stable over a several hour period. The results from slab testing indicate that stable RH measurements can be conducted in as little as three hours after drilling into the concrete, which is a sufficiently small time period for field measurements when the weather is stable and the concrete is not exposed to direct sunlight.

4 CONCLUSION

Results of field tests suggest that the standard procedure for measuring internal relative humidity within concrete stands to be improved. By calibrating probes and monitoring probe behavior in a controlled environment any probe malfunction and degradation over time becomes evident. Calibration data also shows that equilibration time varies with probe type and exposure, affecting the time necessary to make accurate readings. When testing internal relative humidity of in-situ concrete the age of the monitoring port has little effect on the accuracy of readings. Internal RH values are influenced more by port depth and exposure to ambient conditions. Using larger than current standard variations in port depth it may become easier to accurately catalog the changes in internal RH. Additional testing at different depths and different ambient temperatures will be conducted to better understand the humidity gradient within the concrete and the effect of drilling on concrete equilibration time. The current temperature range (21 to 24 degrees Celsius) for RH measurement is restrictive, and information about critical RH values was cataloged over a broad range of temperatures to increase the range of field temperatures at which RH can be measured. The highly reactive aggregate used for measuring critical RH resulted in critical RH values that are not indicative of most concrete found in the field. Therefore, additional testing is being conducted to determine the critical RH for moderately reactive concrete.

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TABLE 1: Relative humidity and temperature testing matrix.

	Relative Humidity			
T (°C)	65	75	85	95
20	$NaNO_2$	NaCl	KCl	KNO_3
30	$NaNO_2$	NaCl	KCl	KNO_3
40	$NaNO_2$	NaCl	KCl	KNO_3
Salt	Sodium Nitrite	Sodium Chloride	Potassium Chloride	Potassium nitrate

**Actual RH values vary with temperature.

TABLE 2: Calibration data for Labjack probes, with standard deviation and difference from the control.

Probe	RH (%)	Stdev	RH (%) Control	Diff.	Probe	RH (%)	Stdev	RH (%) Control	Diff.
1	93.1	0.3	93.0	-0.1	2	90.8	0.3	92.2	1.4
	86.2	0.3	84.2	-2.1		83.3	0.5	83.7	0.4
	74.1	0.2	70.7	-3.4		71.0	0.2	70.5	-0.5
3	92.4	0.3	92.9	0.5	6	95.3	0.2	94.3	-1.0
	85.1	0.1	84.3	-0.8		88.8	0.5	85.5	-3.3
	73.4	0.1	72.3	-1.1		76.8	0.2	70.9	-5.9
7	94.4	0.2	92.9	-1.5	8	93.4	0.2	94.5	1.0
	86.9	0.3	83.9	-3.0		86.7	0.2	85.7	-1.0
	75.7	0.2	70.8	-4.9		73.9	0.2	70.7	-3.2
10	92.6	2.1	93.6	1.0	11	97.7	0.3	97.0	-0.7
	84.7	0.1	84.4	-0.3		88.9	0.2	85.0	-3.9
	75.9	0.1	71.1	-4.8		77.7	0.1	70.7	-7.0
12	90.4	0.1	93.6	3.2	13	87.5	0.8	91.1	3.6
	84.0	0.3	84.9	0.9		82.7	0.2	84.4	1.7
	73.3	0.1	72.7	-0.6		69.4	0.2	69.7	0.3
14	90.3	0.1	92.3	2.1	15	89.7	0.1	92.1	2.4
	84.4	0.1	85.0	0.7		83.3	0.2	85.1	1.7
	69.0	0.1	70.0	1.0		71.1	0.2	69.8	-1.3
16	89.9	0.3	92.2	2.3	17	91.4	0.0	93.6	2.3
	82.4	0.1	84.4	2.0		82.8	0.1	84.1	1.3
	70.4	0.1	72.1	1.7		69.9	0.1	70.0	0.1
18	89.0	0.0	92.9	3.9					
	82.8	0.1	84.9	2.1					
	69.8	0.1	71.6	1.8					

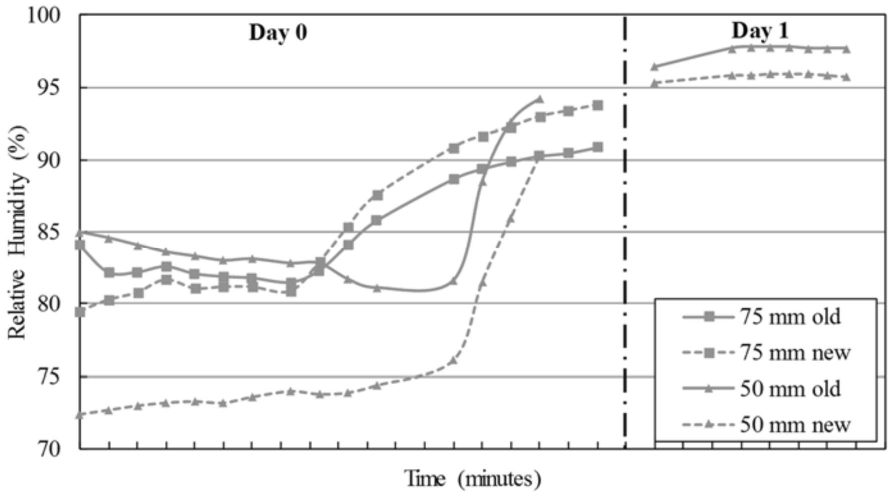

FIGURE 1: Relative humidity (%) with respect to time (minutes) for internal relative humidity of concrete slab 1. Humidity was measured at depths of 50 and 75 mm over a 24-hour period. The humidity ports were drilled into the concrete either one week before measurements (old) or immediately before measurements (new).

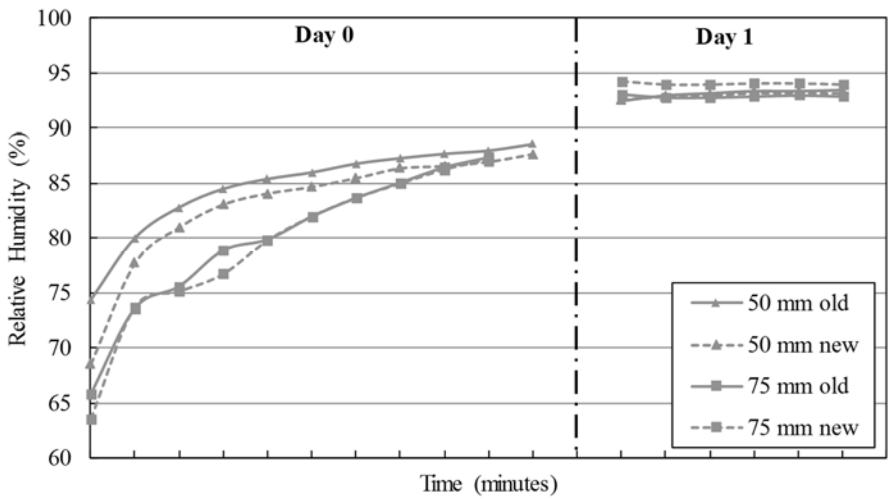

FIGURE 2: Relative humidity (%) with respect to time (minutes) for internal relative humidity of concrete slab 2. Humidity was measured at depths of 50 and 75 mm over a 24-hour period. The humidity ports were drilled into the concrete either one week before measurements (old) or immediately before measurements (new).

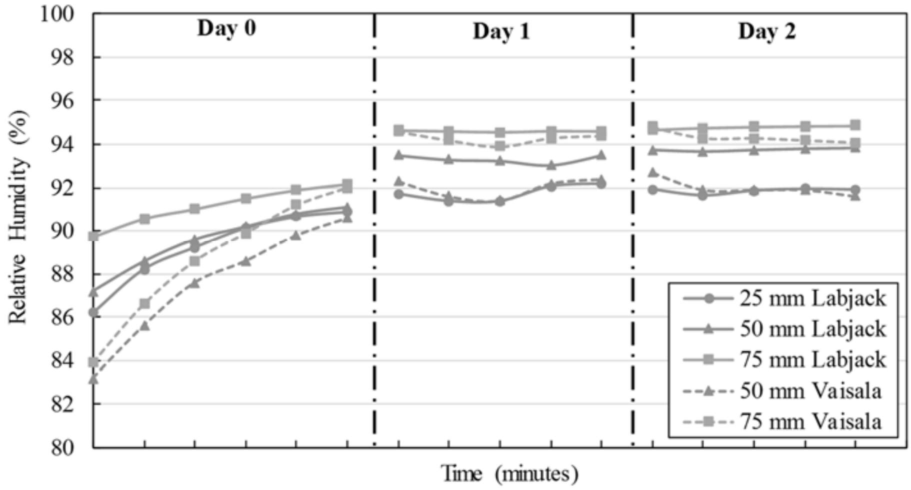

FIGURE 3: Relative humidity (%) with respect to time (minutes) for internal relative humidity of concrete slab 1 rotation 1. Humidity was measured at depths of 25, 50, and 75 mm over a 48-hour period.

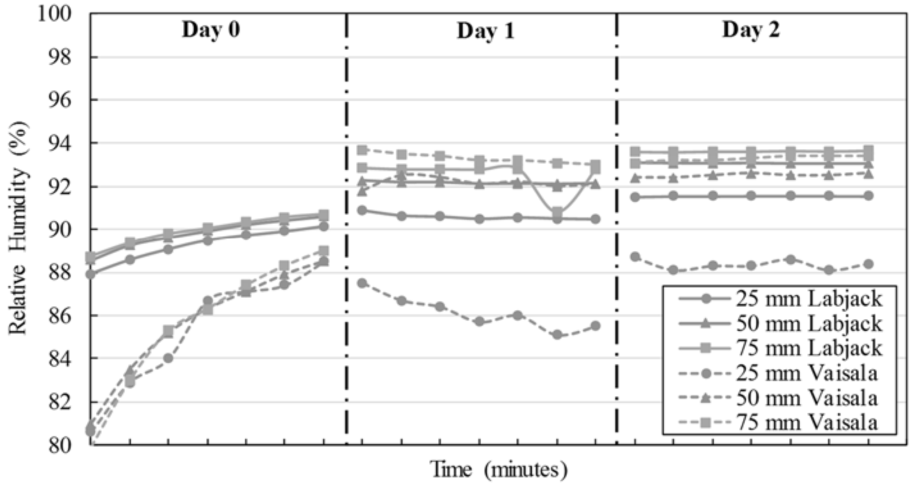

FIGURE 4: Relative humidity (%) with respect to time (minutes) for internal relative humidity of concrete slab 1 rotation 2. Humidity was measured at depths of 25, 50, and 75 mm over a 48-hour period.

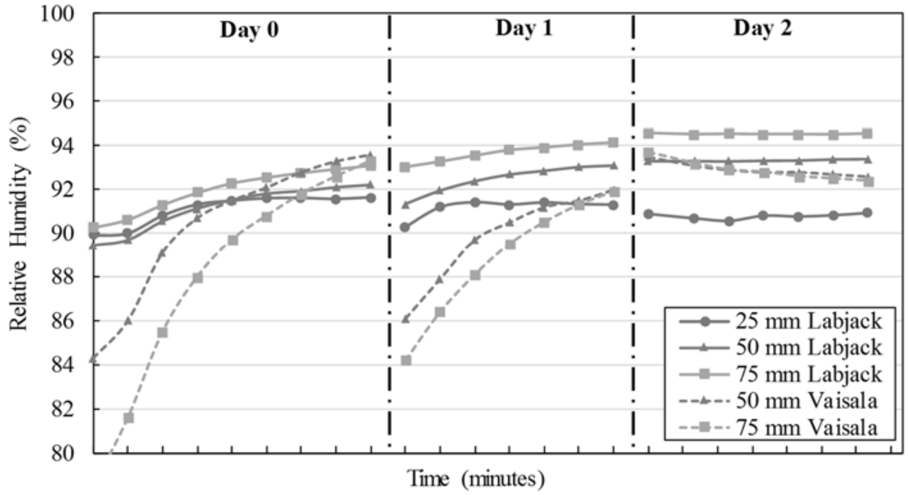

FIGURE 5: Relative humidity (%) with respect to time (minutes) for internal relative humidity of concrete slab 2 rotation 1. Humidity was measured at depths of 25, 50, and 75 mm over a 48-hour period.

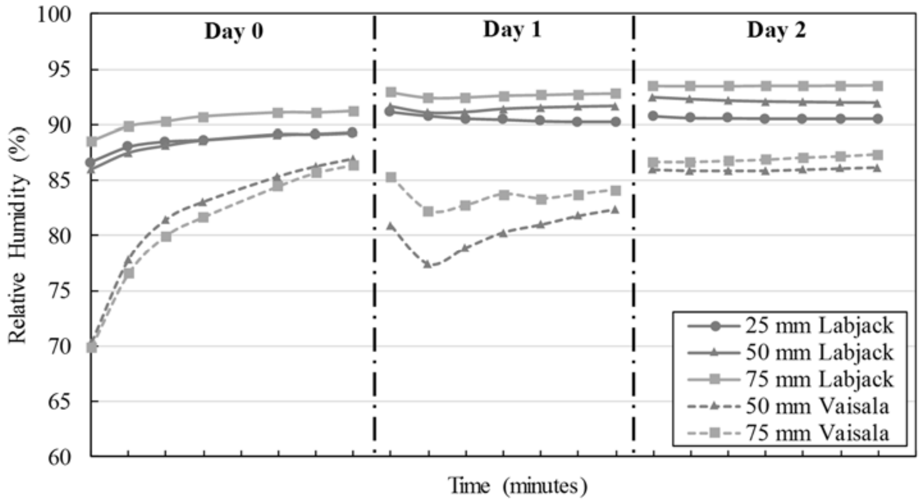

FIGURE 6: Relative humidity (%) with respect to time (minutes) for internal relative humidity of concrete slab 2 rotation 2. Humidity was measured at depths of 25, 50, and 75 mm over a 48-hour period.

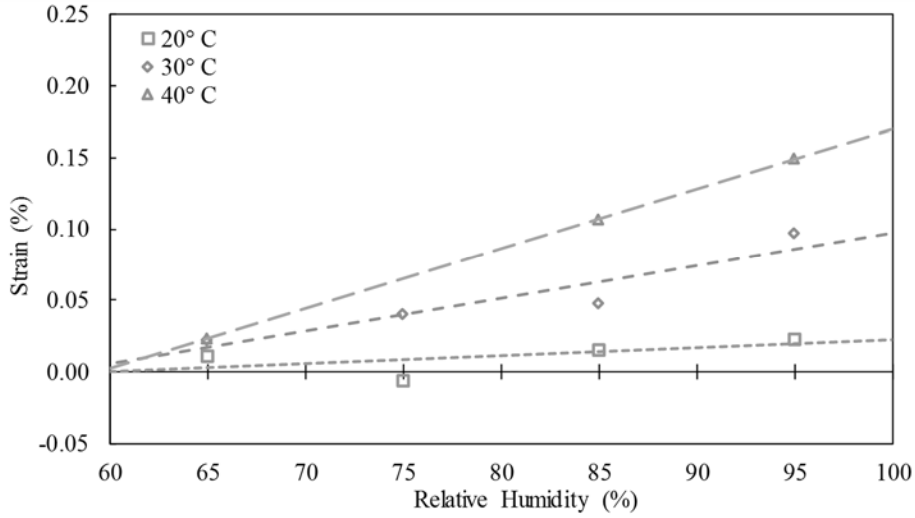

FIGURE 7: Strain (%) measurements with respect to relative humidity (%) of the storage environment. Each sample was stored at a temperature of either 20, 30, or 40 degrees Celsius.