TEMPERATURE EFFECTS ON CONCRETE PAVEMENTS IN OKLAHOMA

By

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TEMPERATURE EFFECTS ON CONCRETE

PAVEMENTS IN OKLAHOMA

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Temperature can have an impact on concrete pavements and can reduce long term performance. When concrete pavements are restrained and temperature changes occur this can lead to cracking. This thesis examines the coefficient of thermal expansion (CTE) of concrete made with aggregates from all major pits in Oklahoma. Lastly, the internal temperature gradients produced by various curing methods were evaluated to investigate the impact on the internal temperatures at setting. This work is critical to the adoption of the MEPDG software for pavement design in the state of Oklahoma.

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CHAPTER I

INTRODUCTION

Concrete is the most commonly used construction material on the planet. It is used for buildings, subways, underwater structures and almost every other type of construction application imaginable but most relevant to this thesis as pavements. Because of its popularity, concrete has previously been, and will continue to be, a widely evaluated construction material.

Concrete, in respect to pavement applications, is placed sometimes in continuous sections as seen in continually reinforced concrete pavements or other times in sections where the section joints are constrained with dowels. Either way, pavements are regularly exposed to the elements and, more importantly for this thesis, temperature changes. As with any material, with changes in temperature come changes in dimension as an effect of expansion and contraction. As a means to evaluate this dimensional change, the coefficient of thermal expansion term exists to quantify the rate at which a material expands or contracts with a given change in temperature. This is an important material property to know so that proper construction practices can be performed to ensure a quality product is provided.

Currently in Oklahoma AASHTO T 336 is used to evaluate the CTE of concrete pavements. This testing method involves taking a sample core and submerging it in a temperature controlled water bath. Subsequently the sample is heated and cooled to known temperatures, and its dimensional change is recorded with linearly variable differential transformers. From this information the

CTE of the sample is calculated. However, measurements are not currently measured in real time, and some previous investigators have seen signal interference randomly appear in their data sets (Won, 2006). Auburn University believed that this interference may be linked to temperature changes being imposed on the LVDT equipment and proposed a modified setup which used ceramics to isolate the LVDT from these temperature changes. Another concern is that since the CTE data is not recorded in real time that the calculated CTE values may contain error without the user knowing it. It is a goal of this thesis to develop a new testing method, modified from AASHTO T 336 and using Auburn Universities temperature isolation practices, which measures deflection change in real time to better ensure the samples have reached temperature equilibrium.

Also of importance to concrete pavements is curing. Curing is any method used to provide water to the concrete to aid hydration and/or to protect the placement from its environment. Curing is important because in addition to these it has the ability to reduce concrete shrinkage related to temperature. In any pavement, a temperature forms throughout its depth which if large can induce curling or warping of the pavement. These deformations can lead to failures which are very costly to repair. Currently various methods exist to cure concrete pavements. It is a goal of this thesis to investigate a number of these method’s abilities to reduce the magnitude of this internal temperature gradient while the concrete is fresh to reduce built in curl in a structure.

CHAPTER II

COMPARISSON OF COEFFICIENT OF THERMAL EXPANSION VALUES OF VARIOUS AGGREGATES IN OKLAHOMA

Introduction

The coefficient of thermal expansion (CTE) is the amount of strain a material experiences for a given change in temperature. The CTE is an important parameter when investigating the performance of a concrete pavement as it contributes to the stresses a concrete pavement experiences from environmental temperature changes. These stresses can be a result of warping and curling, a combination of thermal strains combined with traffic loading, and frictional stresses between the pavement and the sub base.

The CTE of a mature concrete depends on the individual CTE of the paste, fine aggregate, coarse aggregate and the volume each one makes up of the mixture. However, the CTE of a mixture is most influenced by the type of coarse aggregate used, as this material typically makes up around 60% of the volume of the mixture.

The MEPDG software requires the user to input a specific value for CTE. Because of this, it is beneficial to know if a single input value for CTE exists as it could be used in place of multiple specific individual values based on what aggregate pit was used for the project. It is also difficult to determine which aggregate pit was used for any specific project as companies regularly own multiple pits and ship from whichever is more fiscally feasible to them.

A special testing apparatus is described in AASHTO T 336-09 “Standard test method for the coefficient of thermal expansion of hydraulic cement concrete” to investigate the CTE of a concrete specimen. It was necessary to construct a laboratory testing device as the commercial ones available at the beginning of the project had repeatability issues.

Background

Several test methods exist for determining the CTE of concrete. Most widely used is AASHTO TP 60-00 (TP 60). The TP 60 was recently modified and re-designated as AASHTO T 336-09 (T 336) when it was discovered that there was an error regarding the calibration of the testing equipment. (Tanesi, et al. 2010)

T 336

The measurement of CTE with T 336 is achieved by measuring the length change of a saturated concrete specimen as it is subjected to different temperatures. The temperatures required by the method are obtained by using a water bath with a pump to cycle water in the chamber. Deformation of the frame is accounted for by measuring a steel specimen of known CTE in the apparatus. A correction factor is then determined to account for the frame deformation (American Association of State Highway and Transportation Officials 2009).

Prior issues encountered with T 336

Researchers at Auburn University encountered issues with determining the CTE of the same concrete specimens at the same temperatures with different linear variable differential transformers (LVDT) even though the LVDTs were of the same make and model. The Auburn researchers hypothesized that these different CTE values were caused by heat transfer through the components of the testing frame and LVDT. (Sakyi-Bekoe 2008)

Several proposed modifications were made to minimize these effects. These modifications include:

1. A machined ceramic collar (high temperature glass-mica stock) to isolate the LVDT from the cross bar.
2. A machined ceramic spacer (high temperature glass-mica stock) to isolate the tip of the LVDT from the water.
3. A machined Invar cylinder to isolate the ceramic spacer from concrete specimen and water.

These three components are listed in Figure 1.

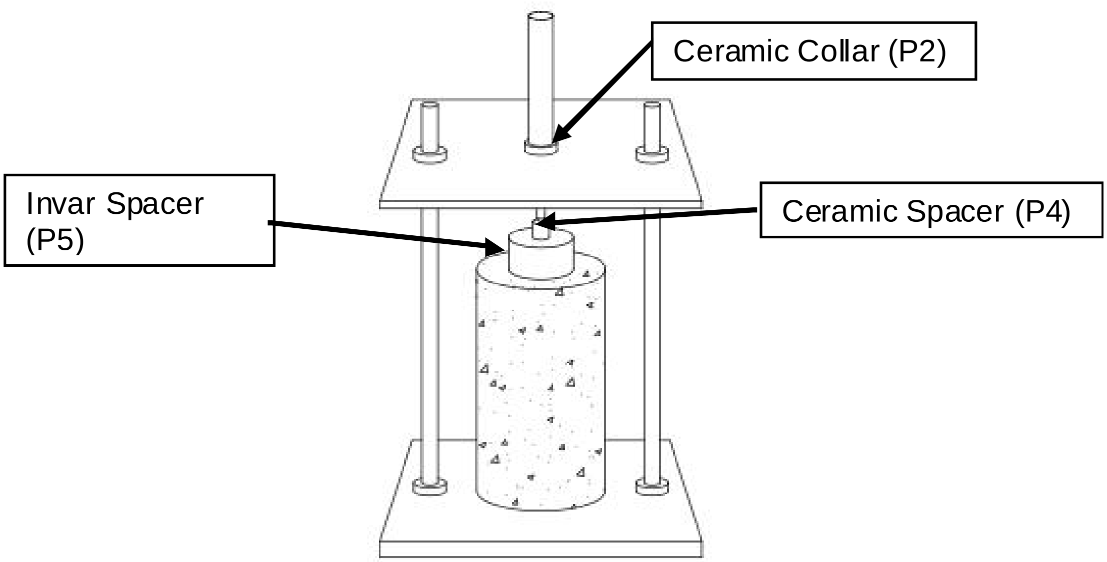

Figure 1: Assembled CTE frame and sample with labels

The "P" designations found in the labels of Figure 1, as well as various other locations in this chapter, represent the component numbering assigned to each individual part of the testing apparatus. These designators are meant to help relate the images to one another as well as associate them with the overall apparatus.

The current test method

In addition to these changes the researchers at OSU felt it was important to have a test setup that was able to continuously measure the length change of the sample. This is not currently required in the test method but proved to be useful.

Currently, in T 336, a sample is cooled to 50°F ± 2°F for a period of time long enough to reach thermal equilibrium in the sample. Thermal equilibrium in the sample is assumed to be reached when constant reading of the LVDT are recorded within 0.00001 inches taken every 10 minutes over a one-half hour period. The measured LVDT length is then recorded and the sample is heated to 122°F ± 2°F until it is at equilibrium and the length is again recorded with the LVDT.

Apparatus

This section details the specific apparatus constructed to evaluate the CTE of concrete cylinders.

Rigid support frame

Figure 2 shows an exploded assembly diagram of the apparatus used to evaluate CTE.

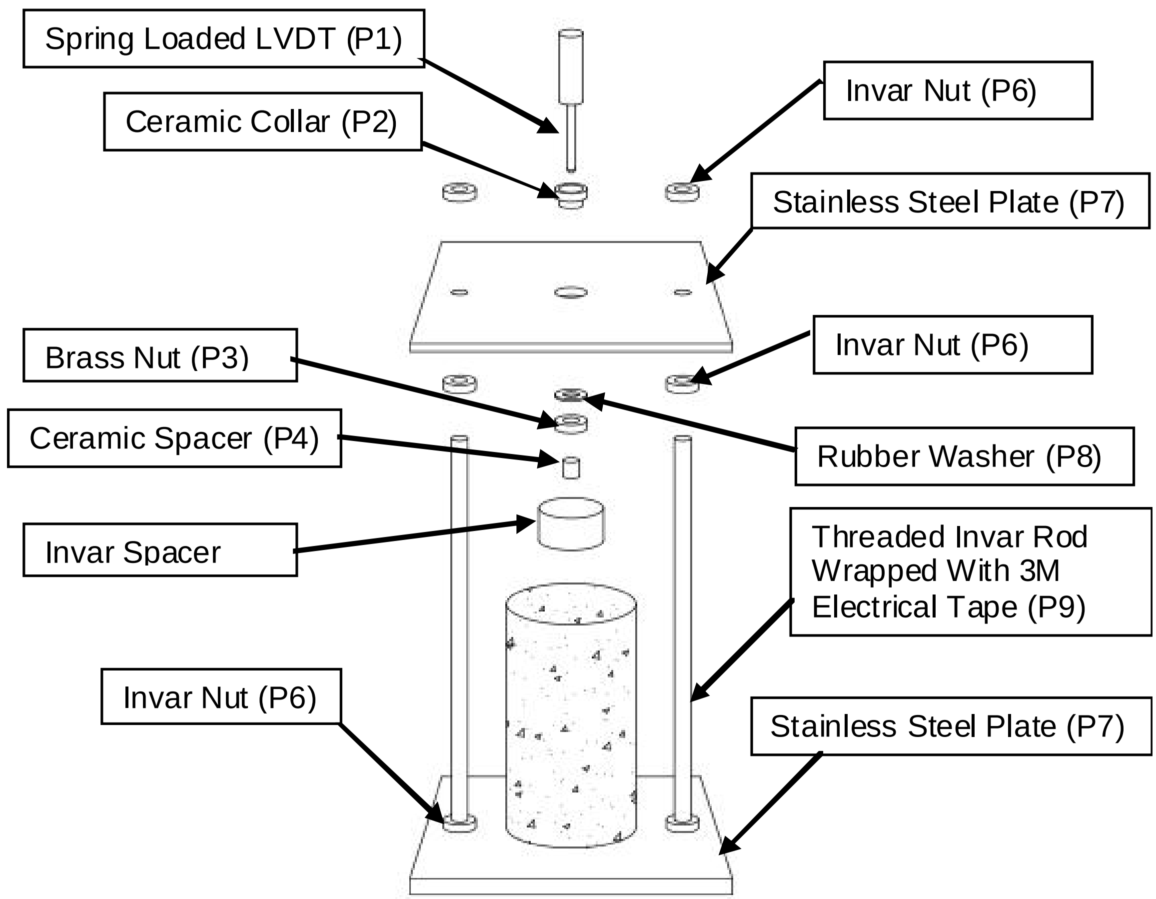

Figure 2: Exploded assembly of CTE frame and sample with labels

Frame

The rigid support frame was constructed in accordance with Appendix X.1 of T 336. The top and bottom plate are stainless steel, while the vertical support rods are machined from Invar. The rods are wrapped with tape for protection against corrosion the full length between the two stainless steel plates. Three semi-spherical support buttons are equally spaced along a 2” diameter about the bottom plate. Figure 3 shows one of the frames prior to placement of an LVDT.

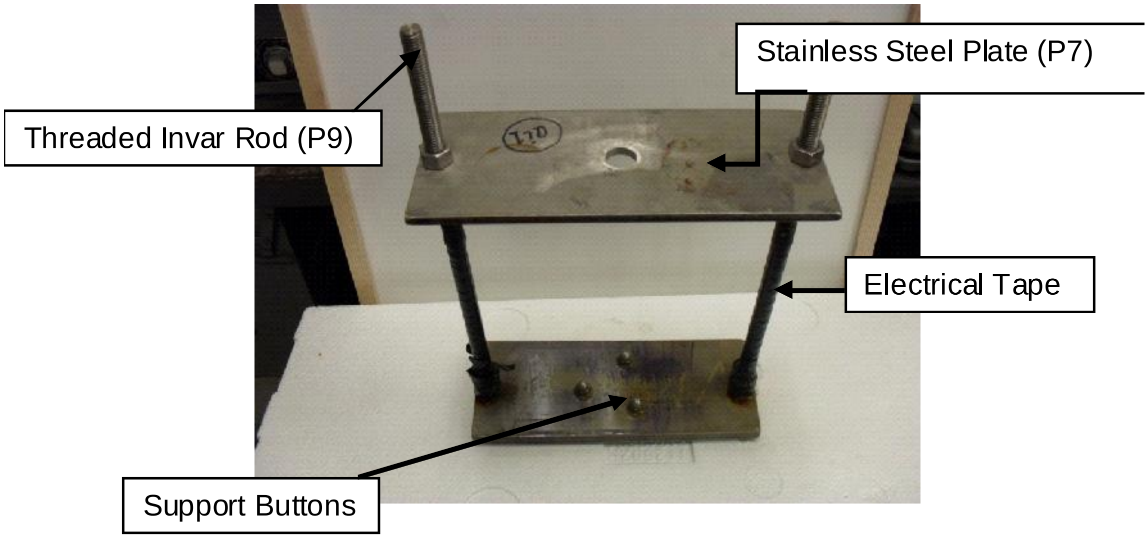

Figure 3: Assembled rigid frame with labels

Ceramic collar

A ceramic collar was used to insulate the LVDT from the top plate of the frame. The collar was threaded to mate with the LVDT. It seats the LVDT in place on the plate with a metal nut and rubber washer and is threaded to match the LVDT. Figure 4 shows on of the ceramic collars constructed by OSU.

Figure 4: Ceramic collar (P2) suggested by Auburn University

Ceramic spacer

A ceramic spacer was machined and positioned concentrically on top of the Invar spacer supporting the piston head of the LVDT. This ceramic spacer is thought to insulate the LVDT from the radiant heat from the water.

Invar spacer

An Invar spacer was machined and positioned concentrically with the concrete cylinder. The Invar is used to separate the LVDT from the surface of the sample and serves as a visible measure of water level within the holding tank. Both the ceramic spacer (P4) and the invar spacer (P5) are marked along their radius to aid in alignment. These can be seen in Figure 5.

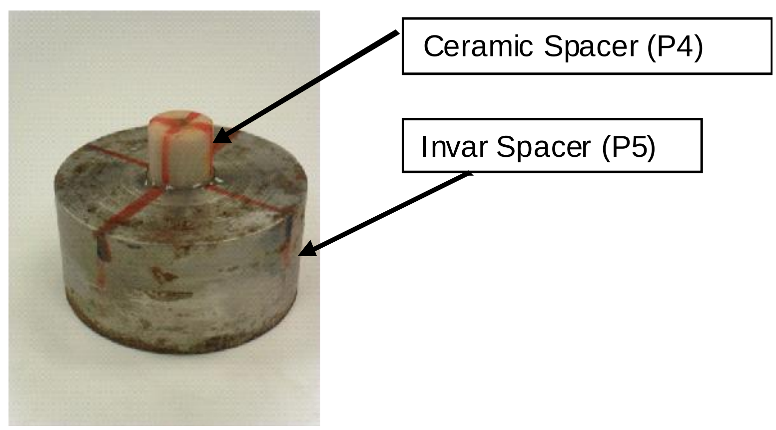

Figure 5: Ceramic spacer (P4) aligned on top of invar spacer (P5)

Water bath

This section details the components used for the water bath.

Circulator

A VWR Signature Heated/Refrigerated water circulator was used for maintaining the desired water temperature within the holding tank. It has a readout accuracy and temperature stability of

±0.25°C and ±0.1°C respectively. The circulator has internal storage large enough to contain a single frame & LVDT assembly. The external holding tank was used by OSU so that two samples could be evaluated at once. The circulator can be seen in Figure 6.

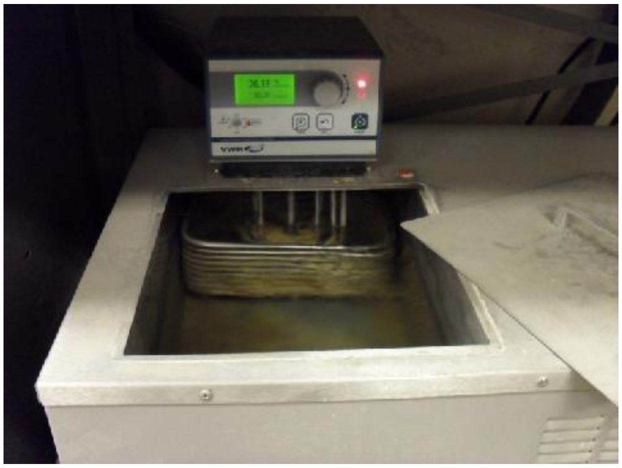

Figure 6: VWR water circulator

Vibration damper

A concrete block was cast in-line with the water out line from the circulator before the holding tank. This mass of concrete reduces vibrations in the water from the circulator before they reach the holding tank. The concrete block was cast around the outlet line between the circulator and the holding tank. Figure 7 shows the vibration damper.

Figure 7: Concrete vibration damper

Holding tank

The holding tank is made from a 10 gallon cooler. The lid has been replaced with a removal wood cover which has a viewing window and openings for the LVDT wiring. The sides of the cooler were tapped to accommodate an inlet and outlet hose for water circulation.

The lid of the holding tank consists of a removable wood frame with a clear plastic viewing window. A rectangular hole was cut in the viewing window to allow the LVDT and wiring to pass through while still providing some insulation to the holding tank. Figure 8 shows the lid of the holding tank. Figure 9 shows the complete CTE assembly and is labeled.

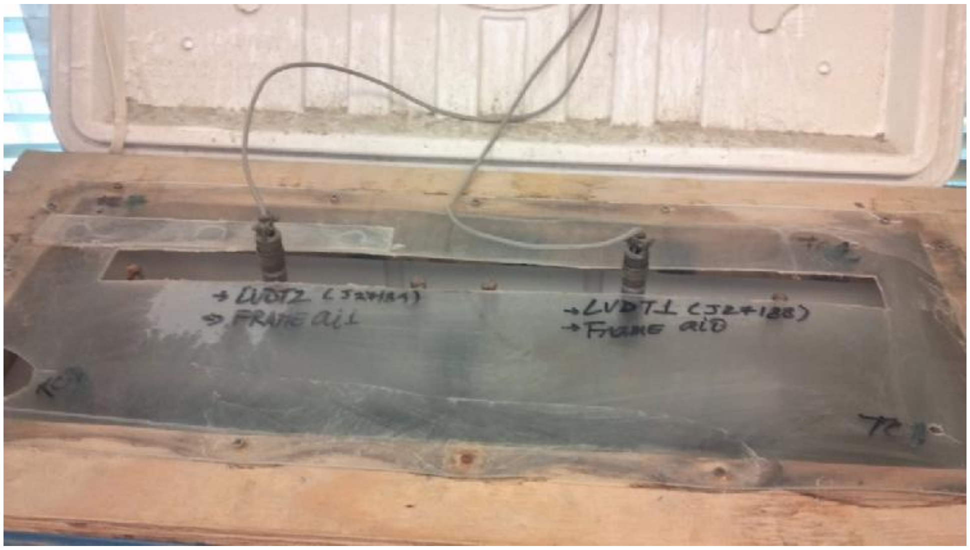

Figure 8: Holding tank lid

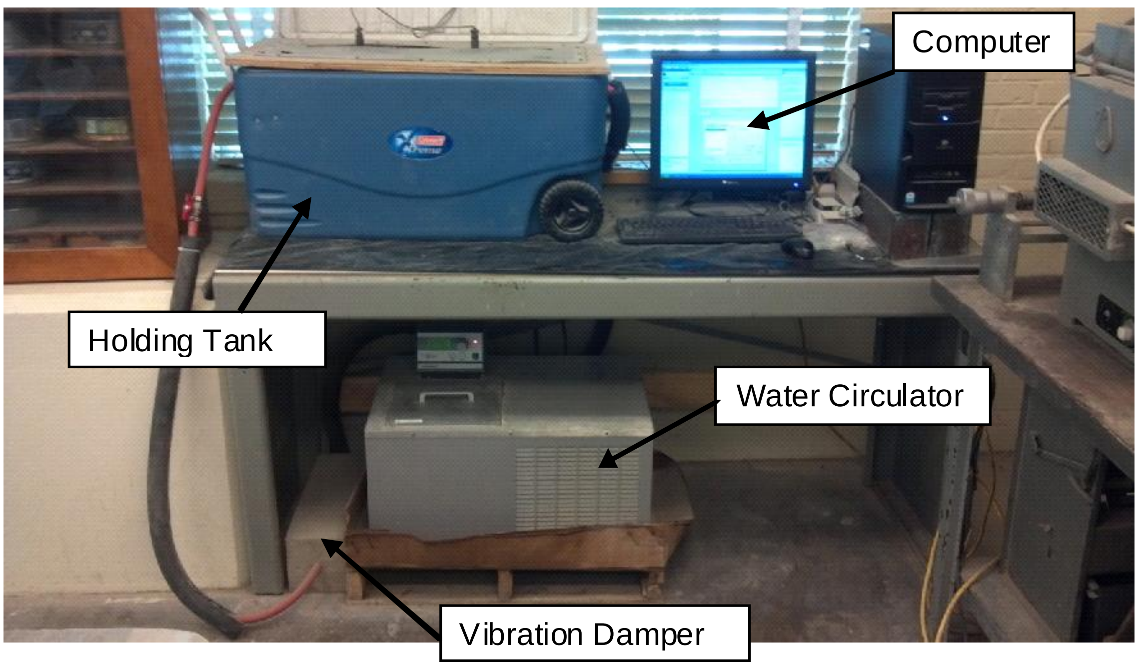

Figure 9: Complete CTE apparatus with labels

Linear variable differential transformer

The GCD-121-125 Schaevitz gage head LVDT. These are DC LVDTs and are of the spring loaded category. This LVDT is widely used by the FHWA, Auburn University, and the University of Texas. Figure 10 shows an image of the gage head LVDT.

Figure 10: Schaevitz LVDT

Signal Carrier

A National Instruments NI USB 9162 C series USB signal carrier was used to connect the LVDT's to the computer software. This was chosen as it allowed a continuous measurement to be taken for both of the LVDTs. The signal carrier allows communication from the LVDT to the computer software. Figure 11 shows the USB carrier used in this experiment.

Figure 11: National Instruments USB signal carrier

LabVIEW software

The software package used to gather and record the voltage data from the LVDTs was LabVIEW 2009. The software allowed output of the voltages into Microsoft Excel spreadsheets for further analysis. Excel spreadsheets were developed at OSU to analyze the signal data from LabVIEW. These spreadsheets make CTE calculations in accordance with T 336.

Methodology

LVDT Calibration

A rigid frame was used to calibrate the LVDTs individually. The LVDT was first placed in the rigid frame and its gauge head was extended to its full length. The voltage at this length was recorded. Figure 12 shows the calibration of an LVDT.

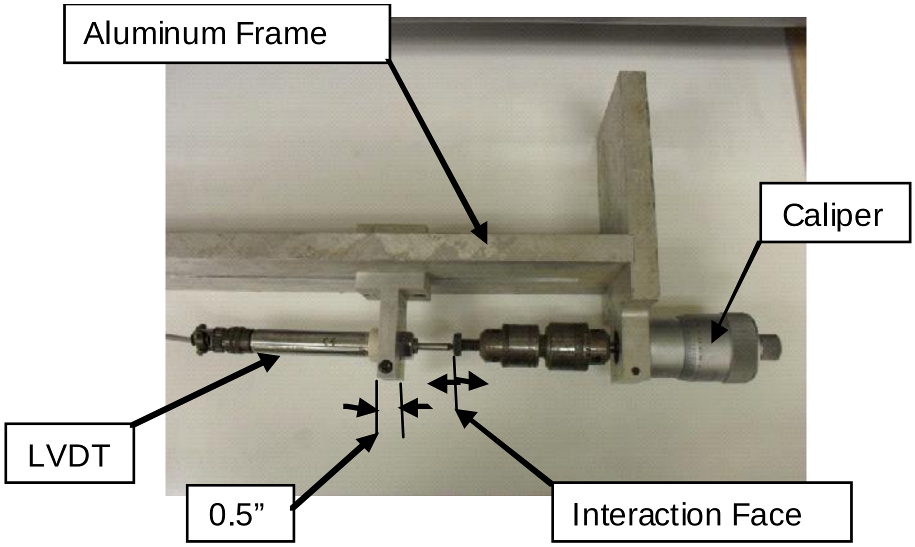

Figure 12: LVDT calibration assembly with LVDT in place

Increasing displacements of 0.025” are imposed on LVDT with a very precise mechanical caliper and their relative voltages recorded. These displacements are made until the gauge head is complete compressed. The data is plotted in a voltage versus displacement graph, and the calibration equations are derived based on the slopes of these lines. Literature suggests that calibration should be done every six months. (Tanesi, et al. 2010)

Figure 13 shows the results of a successful LVDT calibration. The solid line represents actual data recorded while dashed line is the best fit line from which the calibration equation is derived.

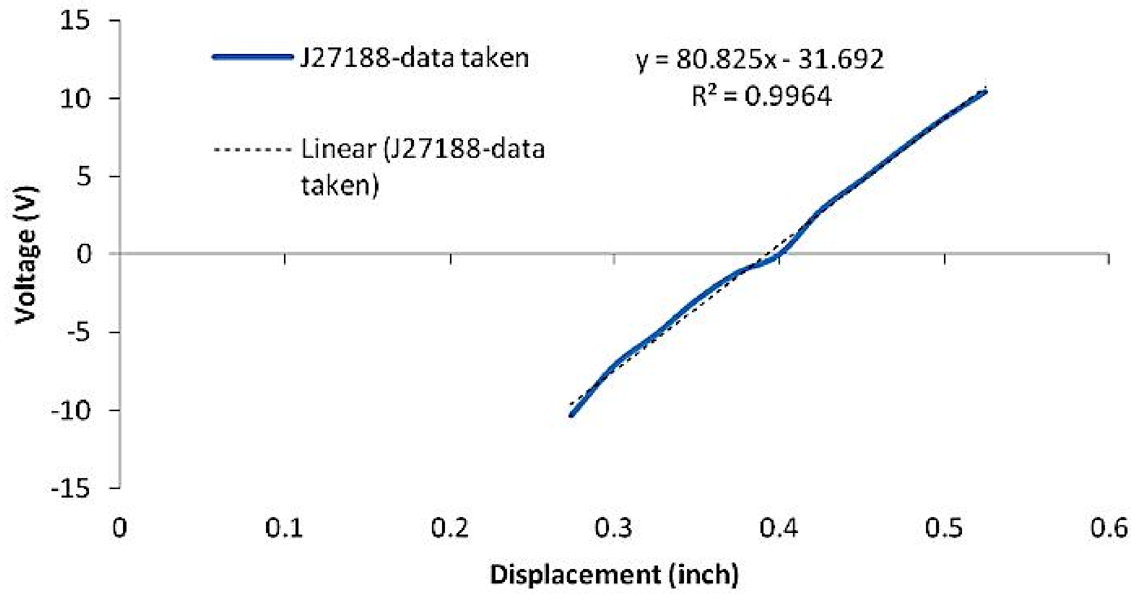

Figure 13: Calibration results from LVDT J27188

Frame calibration

The correction factor for each rigid frame was found in accordance with T 336. A third party laboratory was used to evaluate the CTE of a 410 stainless steel calibration specimen. The same specimen was then evaluated by OSU to determine the correction factor for each frame.

The third party laboratory reported the average CTE as 5.8±0.1x10-6/°F. The specimen was 4” in diameter, 7” in length, and was evaluated in a custom quartz dilatometer in air according to a modified ASTM E228-06. The reported average CTE was calculated as a secant slope of the polynomial regression evaluated at the temperature extremes of 50 and 122°F.

Sample preparation

This section details the steps which take place to prepare the individual samples for testing.

Sample Size

A premeasured jig was used to cut to concrete specimens to a length of 7.0±0.1” with a wet saw. Samples used are 4” diameter concrete cylinders. Table 1 shows a standard mix design used during the CTE sample preparation. All sample mixes were made with the same volume percentages which are based on a typical ODOT concrete pavement design.

Table 1: Typical CTE mix design used for all samples

	Weight (lb)	Volume (%)
Cement	451.2	8.5
Fly Ash	112.8	2.5
Water	231.2	13.7
Rock**	1850	42.3
Sand	1244	28
Air	-	5
Sum	3889.2	100

****value varies*

Sample submersion period

All samples are submerged in a saturated lime water bath for a period no less than 48 hours and until the incremental weight change when measured in 24 hour intervals is less than 0.5% as per T 336.

Sample marking and average length

Samples are marked across their diameter at 45° intervals on the top and bottom faces of the cylinder. A digital caliper is used to take measurements at these intervals around the entire cylinder. These eight measurements are averaged to attain the samples overall average length. Figure 14 shows a sample being measured for average length.

Figure 14: CTE cylinder during measurement with alignment markings

Apparatus preparation

This section details the steps which take place to prepare the water bath and rigid frame prior to sample placement.

Water bath temperature

The water bath temperature is at room temperature at the time when the samples are placed in the reservoir. After sample placement, data recording is begun and the initial ramp temperature is set to 50°F. Samples are evaluated for an interval of 24 hours at which time data is collected and a new ramp at 122°F is begun. The same recording interval is maintained. Two more intervals follow for each sample resulting in two 50°F and two 122°F intervals per sample. This not required in T 336 but was included to ensure that the initial recorded data was repeatable and allows for increased accuracy of the final CTE results.

T 336 currently requires that the samples are heated and then cooled until thermal equilibrium is reached. This equilibrium is described as the condition when consistent readings of the LVDT are recorded to the nearest 0.00001 inch at 10 minute intervals over a half hour period. In this study length measurements were captured every 150 seconds over a 24 hour period per interval measured. This time period was found to be adequate for a sample to reach internal equilibrium at both temperatures based on the results from multiple initial trials.

Figure 16 shows the relation to the deflection readings from a LVDT to the temperature intervals. Notice that it takes anywhere from 5 to 9 hours for the sample to reach equilibrium. Once the sample actually reaches equilibrium, consecutive measurements are taken and averaged so that an accurate value of length can be captured. The 24 hour period is long enough to always ensure equilibrium within the sample and provide sufficient data for accurate length measurements.

Sample placement

Samples are placed concentrically with the center of the LVDT and the three support buttons on the bottom plate of the rigid frame. On top of the sample are the Invar and ceramic spacers. Alignment markers placed along the diameters of both spacers and the sample allow for proper alignment. Figure 27 shows the alignment of the components and a sample.

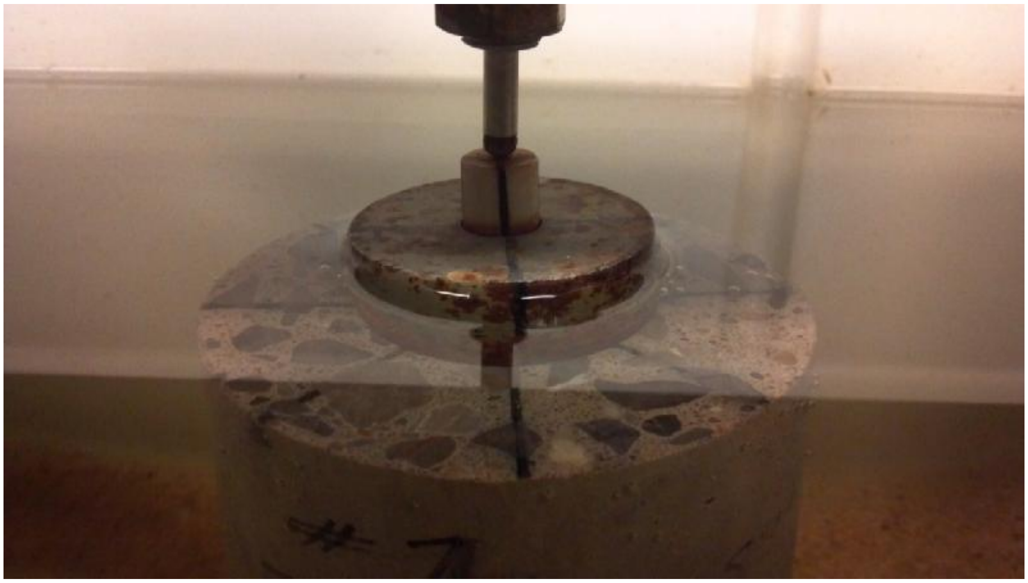

Figure 15: Aligned LVDT, ceramic spacer, invar spacer and sample in the holding tank

Software execution

The LabVIEW software begins recording LVDT voltages at 150 second intervals once the samples have been properly placed and the water bath program had been initiated. After the 24 hour recording period is reached, voltage data is exported to Microsoft Excel. This is the procedure for a single ramp and is repeated three times for all of the samples investigated.

Data analysis

Once data has been collected from LabVIEW, the voltages are converted into deflections with the conversion formulas for each LVDT. These deflections are then entered in to Microsoft Excel for analysis as per T 336.

Any noise interference is filtered out of the data by using the filter function imbedded in Excel. This unknown interference is seen on every set of data and has been seen previously by other researchers that have used the same equipment. (Won 2006)

To filter the data, the deflection readings prior to equilibrium should be removed as well as the majority of the visible interference. This provides a rough data set which is a good representation of the actual deflection readings and is followed by a second filtering procedure to further refine the data. Figures 16 and 17 show deflection data before and after the first filtering process respectively.

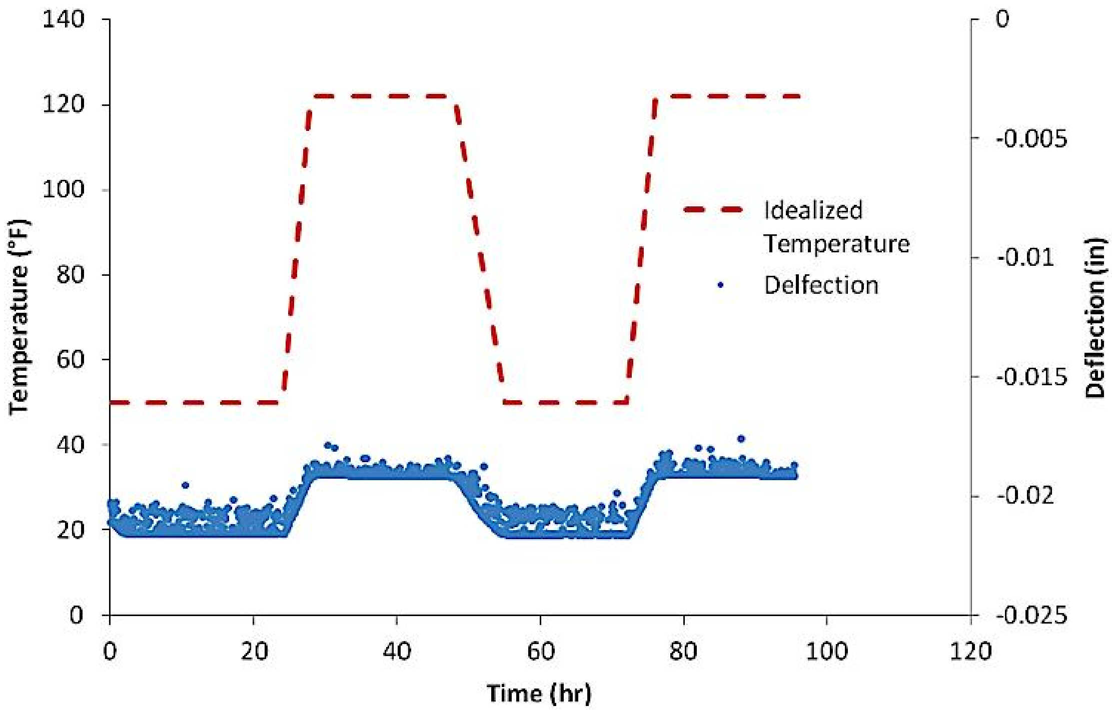

Figure 16: Deflection data prior to the first filtering process

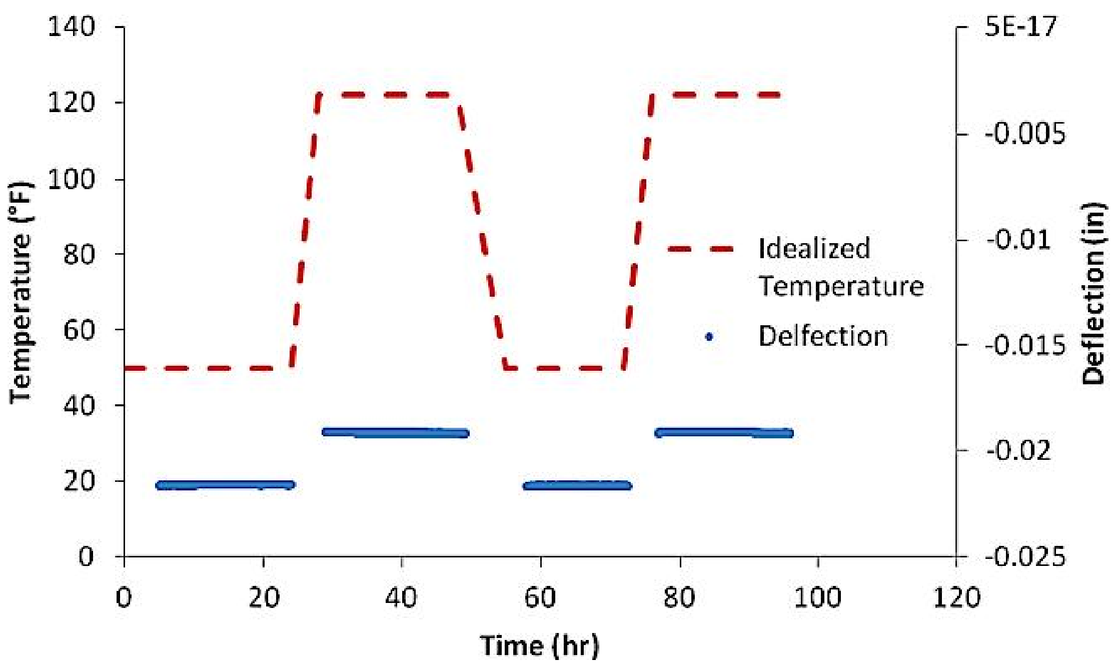

Figure 17: Deflection data after the first filtering process

The second filtering process consists of taking the difference between each data point. Only data points showing a difference of 0.00002 inches are kept for further use. This is done to ensure that the deflections used for CTE evaluation are as similar as possible.

After the second filtering process, the deflections are averaged to attain representative sample lengths at each temperature extreme. Each sample undergoes four temperature extremes which make up three temperature ramps as previously described. The average lengths determined at each temperature extreme are then used to calculate the length change the sample undergoes during each ramp.

The need for filtering may not have been experienced in previous CTE testing methods since intervals of 150 seconds were not used for continuous monitoring. With the mentioned filtering procedures there was high confidence in the results. This can be seen in the low coefficients of variance for each trial.

The three ramps are used to calculate three CTE values, as per T 336, for each sample. This is done to ensure that average CTE value is accurate and has a low coefficient of variance.

Results

Table 2 is comprised of all samples evaluated and their average CTE values. The table also includes other relevant information about the aggregates used in each sample. Notice the extremely low coefficients of variance.

Table 2: CTE testing results and sample information for all samples tested

Sample	Mineralogy	Abs. (%)	SG (SSD)	Dry Rodded Unit Weight (lb/ft^3)	Avg. CTE (10^{-6}/°F)	Frame	CTE (10^{-6}/°F)	Diff. between frames (10^{-6}/°F)	Std. Dev. (10^{-6}/°F)	COV (%)
Coleman	Dolomitic Limestone	0.55	2.77	173.1	5.3	0	5.2	0.2	0.044	0.85
						1	5.4		0.034	0.62
Cooperton	Dolomitic Limestone	0.92	2.81	147	5.2	0	5.2	0.1	0.028	0.54
						1	5.1		0.11	2.17
Davis	Rhyolite	0.64	2.71	165.6	5.5	0	5.2	0.6	0.062	1.19
						1	5.8		0.17	2.85
Drumwright	Limestone	0.52	2.71	168	5.6	0	5.39	0.3	0.017	0.32
						1	5.71		0.16	2.78
Hartshorn	Limestone	1.13	2.62	169.2	4.5	0	4.5	0	0.054	1.2
						1	4.5		0.098	2.18
N. Troy	Limestone	1.45	2.71	171	5.6	0	5.5	0.2	0.019	0.34
						1	5.7		0.12	2.13
OKAY	Limy Sandstone	3.06	2.51	155.1	5.5	0	5.3	0.4	0.25	4.75
						1	5.7		0.082	1.44
Sawyer	Sandstone	2.02	2.52	156.1	6.8	0	6.9	0.3	0.23	3.4
						1	6.6		0.12	1.84
Richard Spurr (5.5 Sack)	Limestone	0.89	2.67	168.1	5	0	4.7	0.5	0.021	0.44
						1	5.2		0.054	1.04
Ricahrd Spurr	Limestone	0.89	2.67	168.1	5.1	0	4.9	0.4	0.017	0.35
						1	5.3		0.051	0.96
Richard Spurr (6.5 Sack)	Limestone	0.89	2.67	168.1	5.1	0	4.9	0.3	0.034	0.7
						1	5.2		0.035	0.67

Also, note that there is not a noticeable CTE difference between the three Richard Spur samples. These three samples vary in paste content and their results suggest that the CTE value is not greatly dependent on paste content, at least for these mixtures.

Discussion

When comparing the average CTE values in Figure 18 it can be seen that the majority of the samples are between 5 and 5.5x10-6/°F. Removing the two outliers (Hartshorn and Sawyer), the average CTE value is 5.4x10-6/°F. This value is representative of all aggregates except Sawyer, sandstone, which has a higher Average CTE of 6.8x10-6/°F. Hartshorn is a limestone which showed a low average CTE of 4.5x10-6/°F. Figure 18 shows all CTE values plotted against each other and the average representative CTE. The samples are ordered in relation to this graph on Table 2.

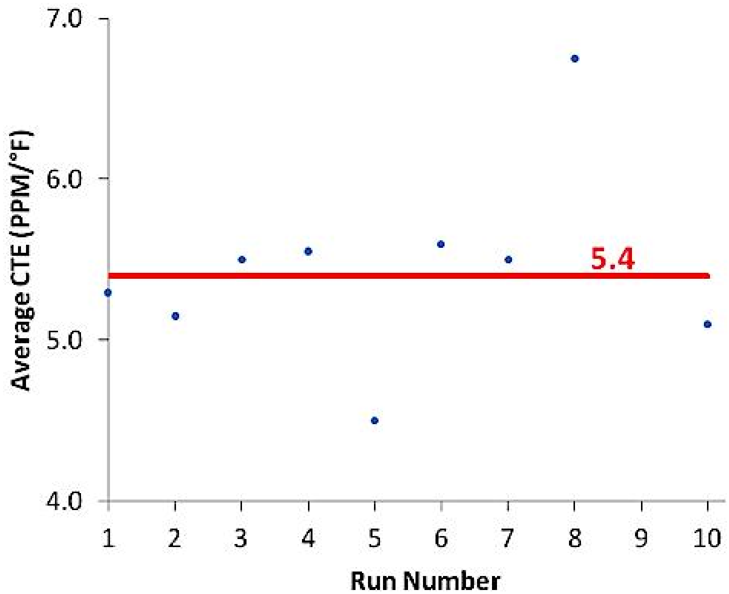

Figure 18: Individual CTE comparison of all samples with overall average CTE value

Geometry Change

Random changes in LVDT readings were seen in some samples during the testing. These changes can be seen in the Figure 19 below as non-typical areas.

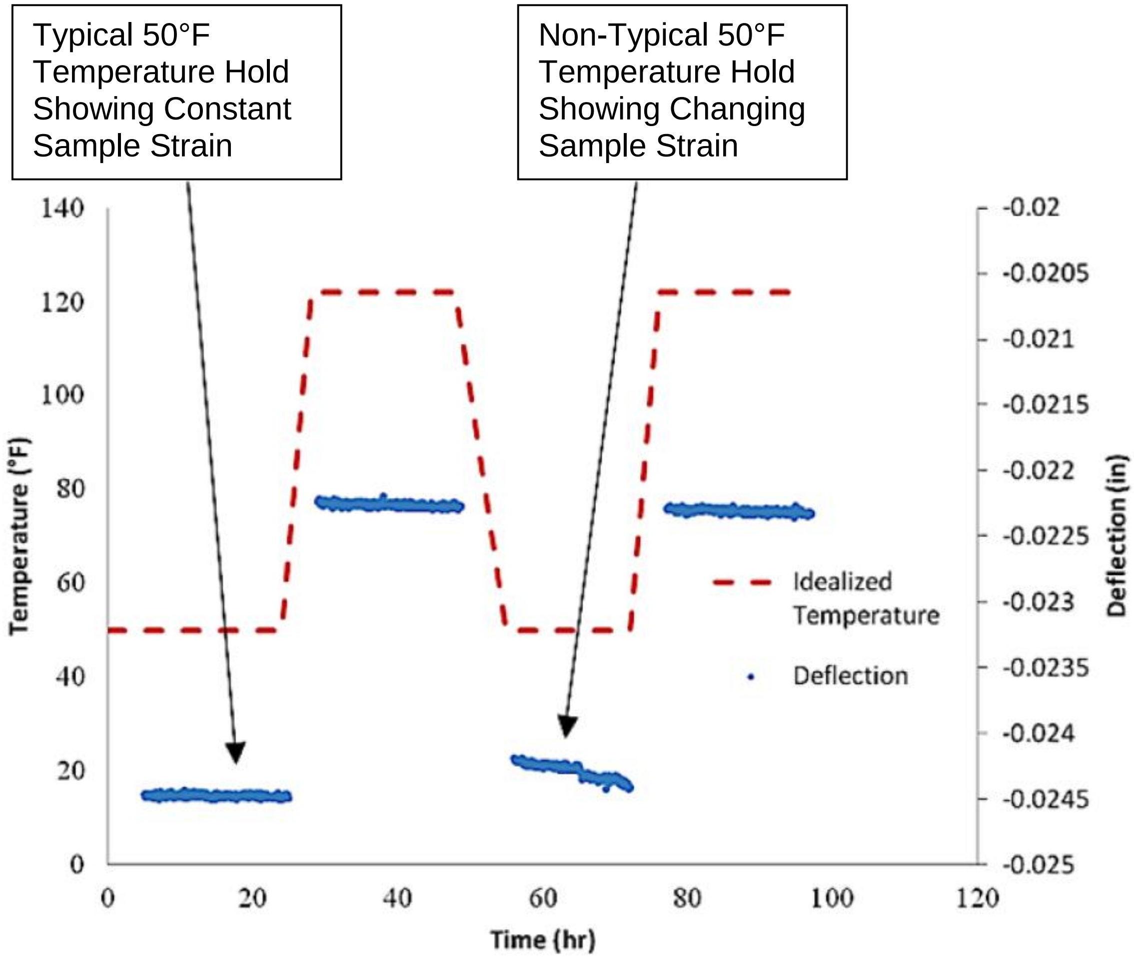

Figure 19: Filtered non-constant geometry

The witnessed change comes in the form of a non-uniform strain pattern where one should be present. It is believed that this is due to the LVDT device. When non-typical deflection data were encountered, the sample was re-tested until typical data was collected for the entire dataset. This was done to ensure that the data was not tainted in any way by suspected LVDT errors. These non-typical changes happened at random so it was important to check the unfiltered datasets before CTE evaluation for non-typical data for every sample. This observation would not have been made if the LVDT was not continuously measured.

These errors were encountered on 8 of the 11 investigated samples and so were frequent. When this occurred the data was repeated.

Recommendations

The modified version of the CTE test method developed at Auburn with modifications by showed consistent and repeatable results. This is proven by the low coefficient of variation values.

It appears that the modifications to the apparatus made to isolate the LVDT from varying temperatures was helpful and should be incorporated into future versions of this test.

Measurement intervals at 150 second periods over multiple 24 hour intervals at varying temperatures should be strongly considered in future testing. This ensures that errors in testing are not made and that true sample equilibrium is reached for accurate CTE evaluation.

Filtering of the deflection data prior to CTE evaluation is needed to ensure accurate evaluation of the sample. The interference seen during the continuous monitoring of the samples can greatly influence the calculated CTE of any given sample if it is not removed.

The use of multiple frames is also suggested. Testing samples in different frames and comparing CTE values between the two also help minimize errors.

Random changes in length recorded by the LVDT have been noticed during this testing. The source of these changes is unknown and would not have been observed if continuous measurement was not used. These errors occurred frequently and caused samples to have to be retested.

Recommendation of impact of aggregate type on CTE

One useful finding from the work is that the majority of the CTE values were similar in value. As shown in Table 2 of the nine different aggregates investigated, seven of them were between 4x10-

6/°F and 5.45x10-6/°F. This means that a value 5.4x10-6/°F is a strong representation of the CTE of all pits in Oklahoma excluding Hartshorn and Sawyer. This being said, internal stresses due to varying CTE values of different aggregates does not have to be taken into concern since it is a relatively constant value throughout the state.

CHAPTER III

IMPACT OF CURING METHODS ON EARLY AGE TEMPERATURES IN CONCRETE

Introduction

Internal temperature gradients in concrete are influenced by many conditions both material and environmental. In pavements these temperature gradients can cause curling and warping of the placement. One way to minimize this deformation is to insulate the pavement from environmental temperatures during curing. To evaluate these gradients, various curing techniques were compared side by side to evaluate the impact each had in effecting the internal temperature gradients.

Apparatus

Collapsible wood forms were used that are 36”x36”x8”. The earth beneath the forms was turned, compacted by hand, and leveled. Once the form was assembled and leveled off, sand was used to fill the bottom so that an 8” sample depth was achieved.

A wooden thermocouple stake was used to support the thermocouples in the fresh concrete. This was made by taking a surveying dowel with three 0.25” diameter holes at depths of 0.5”, 4.0” and 7.5” from the top of the sample. Figure 20 shows a wood dowel that is ready for use.

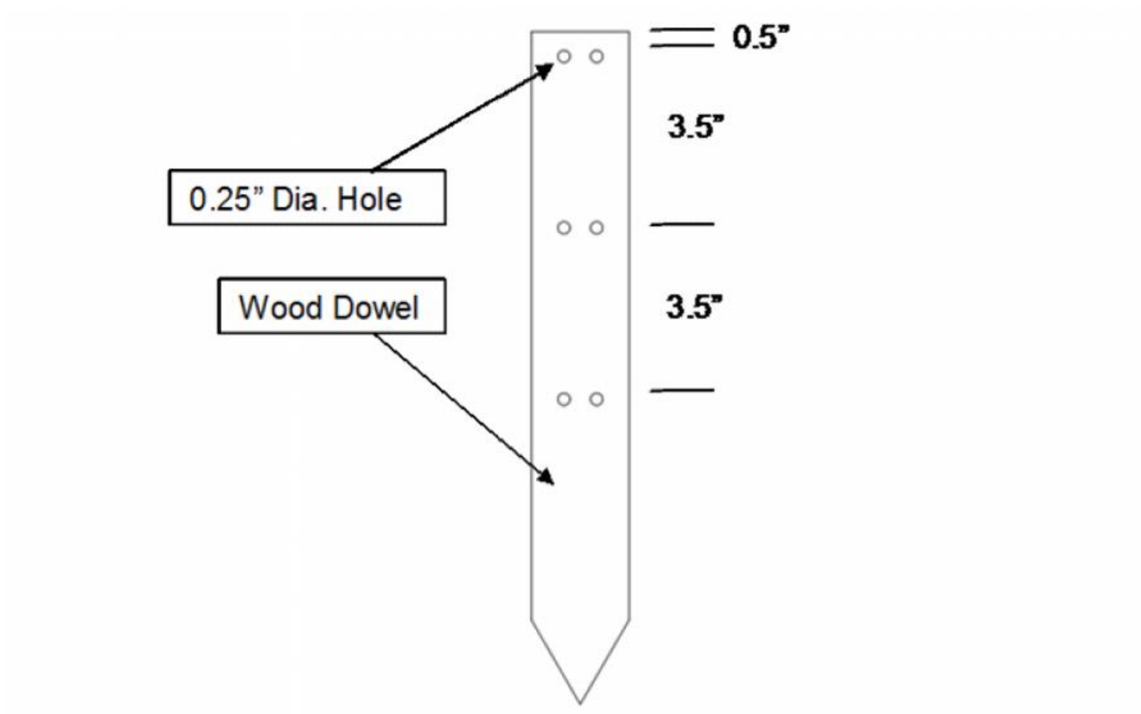

Figure 20: Wood dowel with dimensions

The dowels are hammered into the ground at the center of the form. The tops of the dowels were leveled with tops of the wood forms. Six temperature measurements were taken per sample for redundancy. Figure 21 shows the image of a completed assembly with labels.

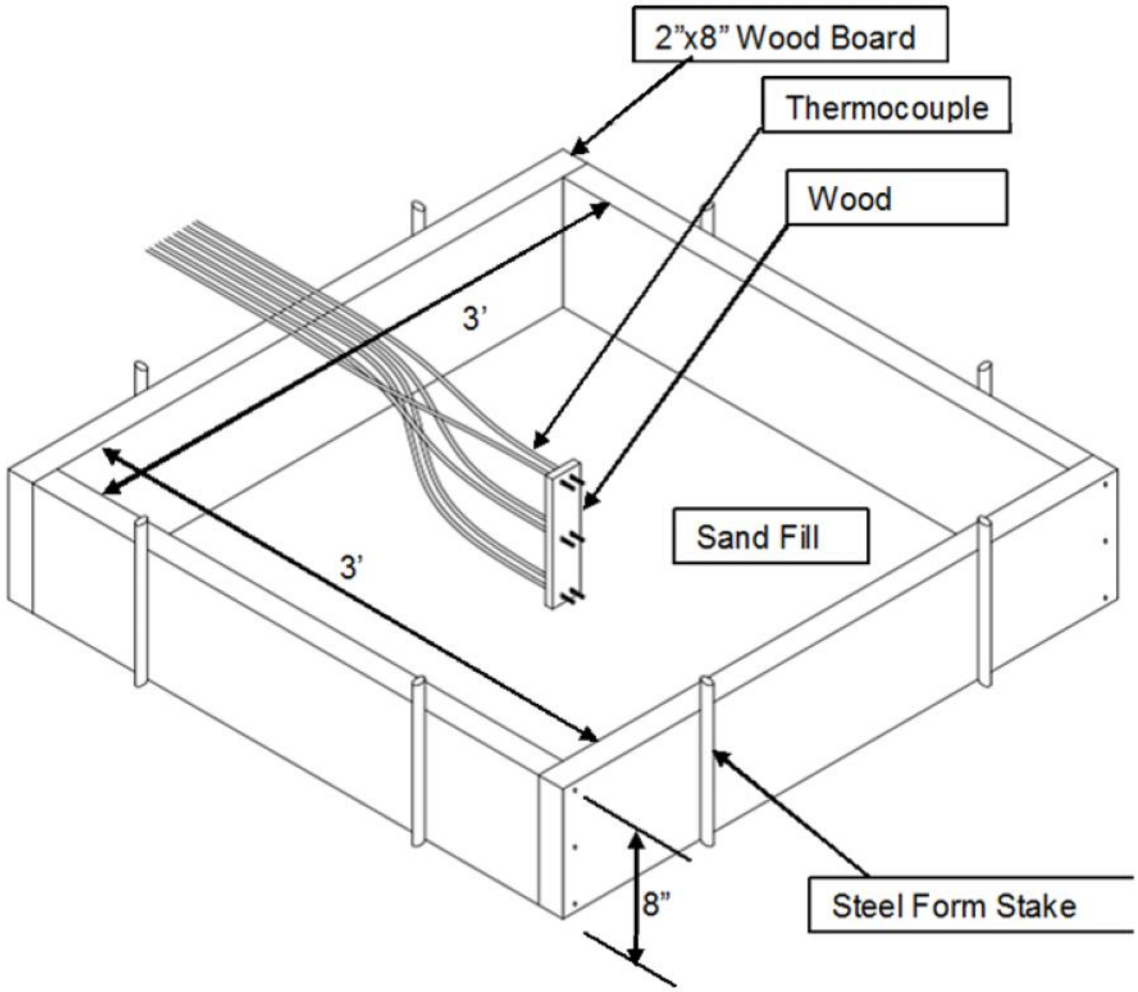

Figure 21: Assembled thermocouple, dowel & form

The mixture was ordered from a local batch plant and the concrete was delivered to the site. The mixture was a 4000 psi, 2" slump pavement concrete.

The samples were placed with two lifts. After each lift, the sample was vibrated. Once the two lifts are in place, the samples were finished to the surface of the form.

After the samples were finished, the curing methods were applied.

Results and discussion

A temperature differential at different time periods was measured for each sample. Ideally, a curing method should produce a near uniform temperature differential throughout the depth of the sample. This will minimize the temperature differential at setting and minimize the idealized built in curl in the concrete.

The time intervals presented in the following figures are approximate to account for the time required for the concrete to arrive from the batch plant and the samples to be made and curing methods applied. It is assumed that the hourly time intervals presented in the results begin approximately two hours after the concrete was produced at the batch plant.

Curing methods tested

Three investigations were made consisting of varying combinations of curing methods.

The methods investigated and reported here are:

1. No cure
2. Misting
3. One layer of curing compound
4. One layer of wet burlap
5. One layer of wet burlap covered by one layer of clear plastic

These investigations took place on three separate days each having noticeably differing outside temperatures. These days had different mean temperatures that allowed different conditions to be compared. These trial dates coincide with summer fall and winter conditions.

On the following figures, there are dashed lines which represent temperatures at various depths of the sample. The two lines named "air" and "ground" represent the ambient air and ground temperatures above and beneath the sample. To measure the ambient air condition, a thermocouple was suspended three feet above the samples exposed to the environment. To measure the ambient ground temperature, a thermocouple was buried six inches below ground surface. Also, the figures present data at hourly intervals which are differentiated by color as seen in the figure legends.

No curing

Figures 22, 23 and 24 present the no cure sample data for the three trial dates.

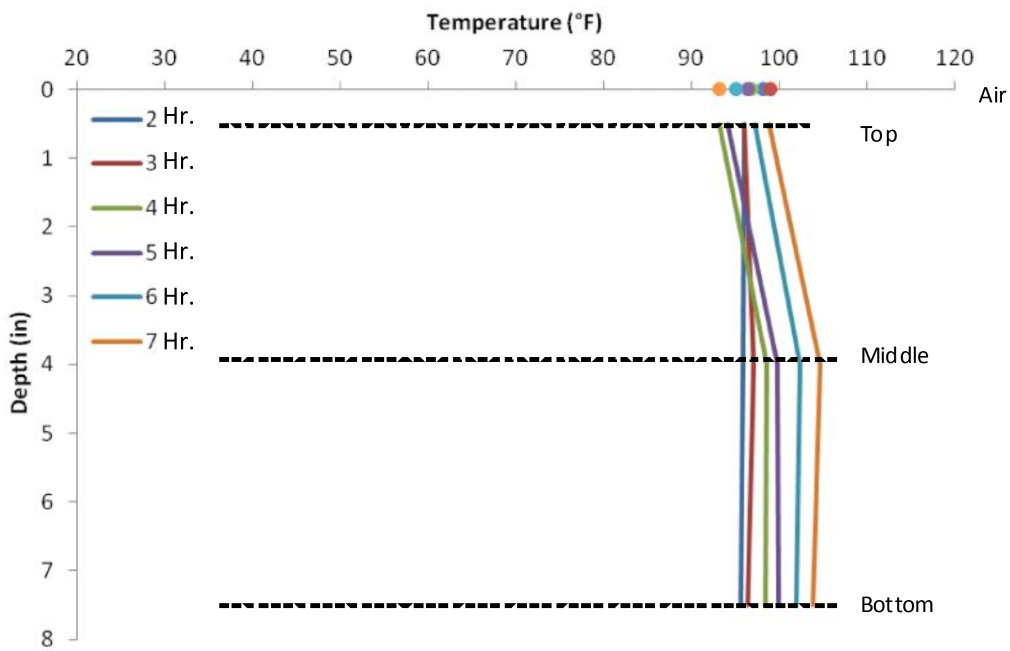

Figure 22: August 29, 2011 (summer) no cure temperature differentials

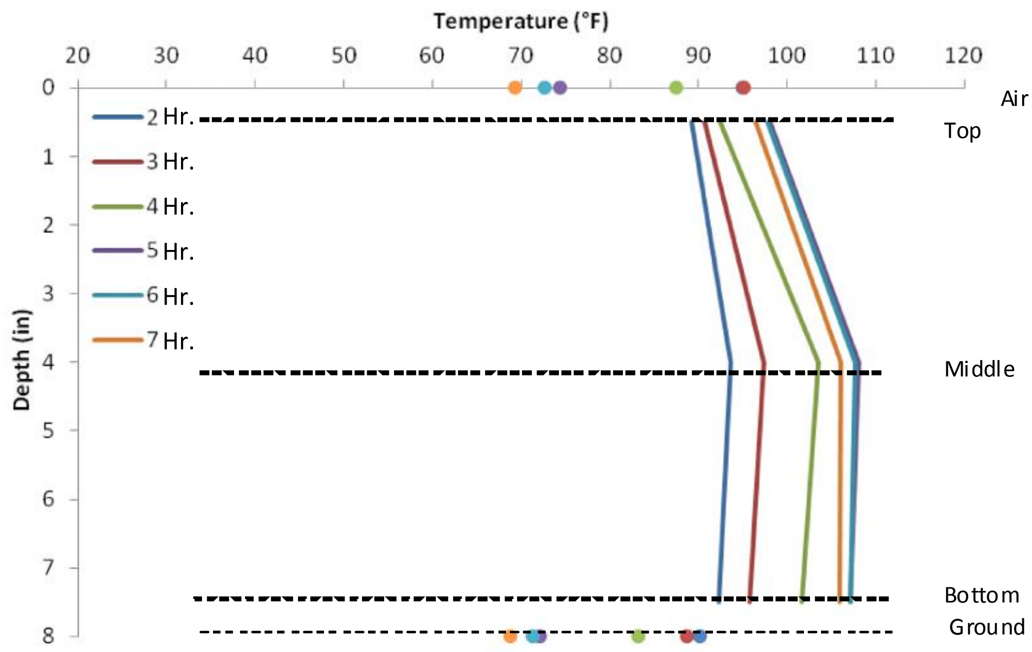

Figure 23: October 4, 2011 (fall) no cure temperature differentials

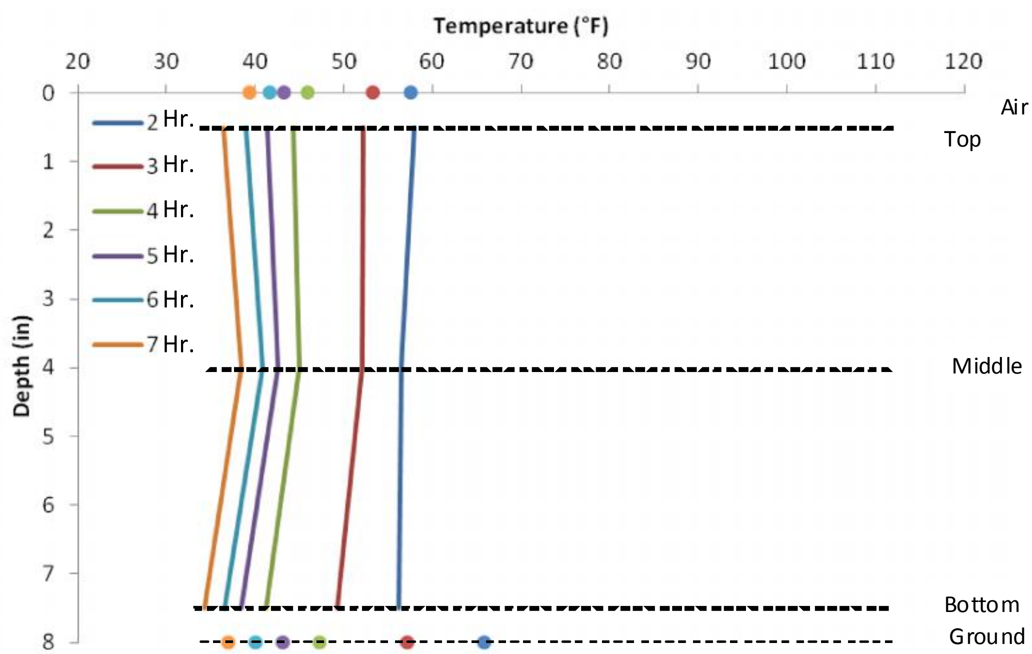

Figure 24: November 30, 2011 (winter) no cure temperature differentials

This method is considered the benchmark between all of the other tests. Conventionally this is thought to be the worst curing situation. The samples where no curing techniques were used showed that initially the samples surface remained cooler than the ground temperature. At four hours, the greatest difference in the temperature at the surface versus the rest of the sample can be seen. Afterward the sample begins to cool in a relatively uniform manner as the surrounding temperatures decreased.

Misting

Figures 25 and 26 present the trial data where hourly misting was used.

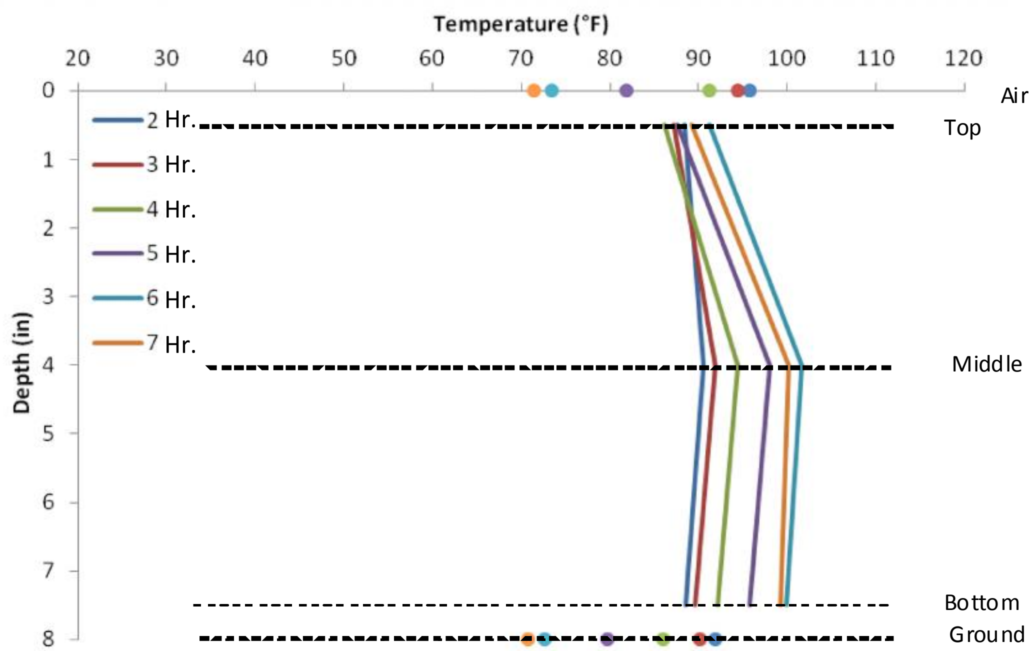

Figure 25: October 4, 2011 (fall) slab placed and cured with hourly misting

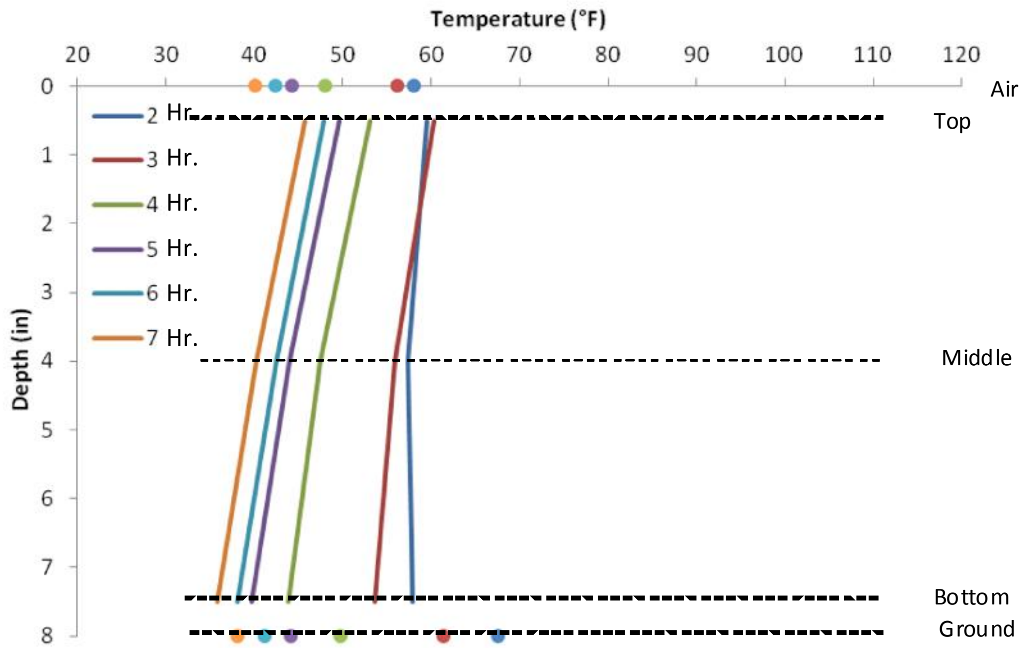

Figure 26: November 30, 2011 (winter) slab placed and cured with hourly misting

A fine water spray was applied to the sample surface of the sample once per hour for six hours after placement. There is no noticeable difference between the no curing and the misting sample. This is likely because the misting is not a large enough volume to make an impact on the mass of concrete.

Curing compound

Figures 27 and 28 present the data for the single layer of Oklahoma curing compound trials.

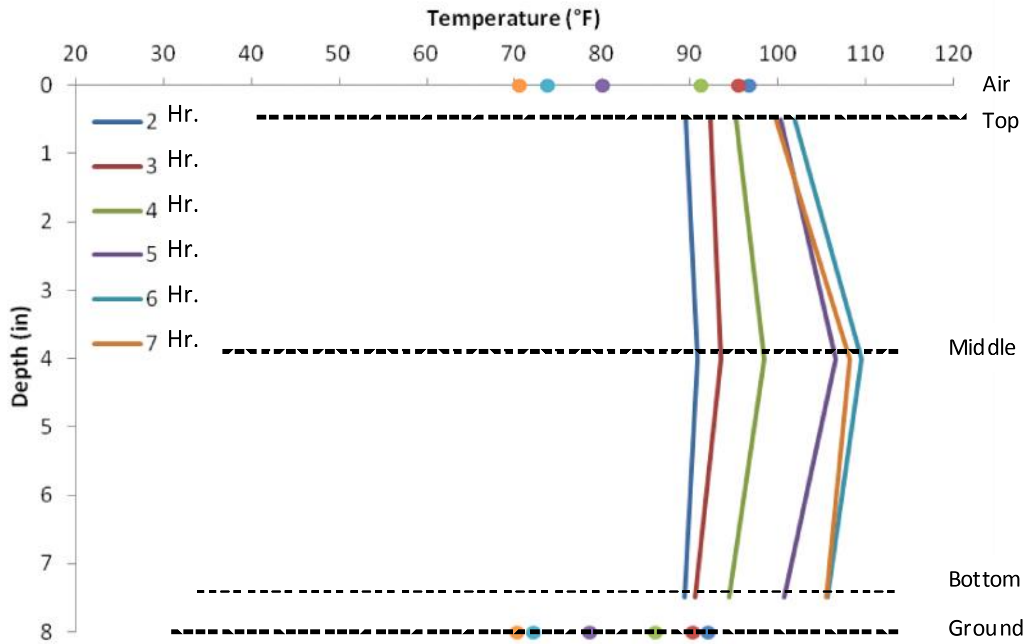

Figure 27: October 4, 2011 (fall) single layer curing compound temperature differentials

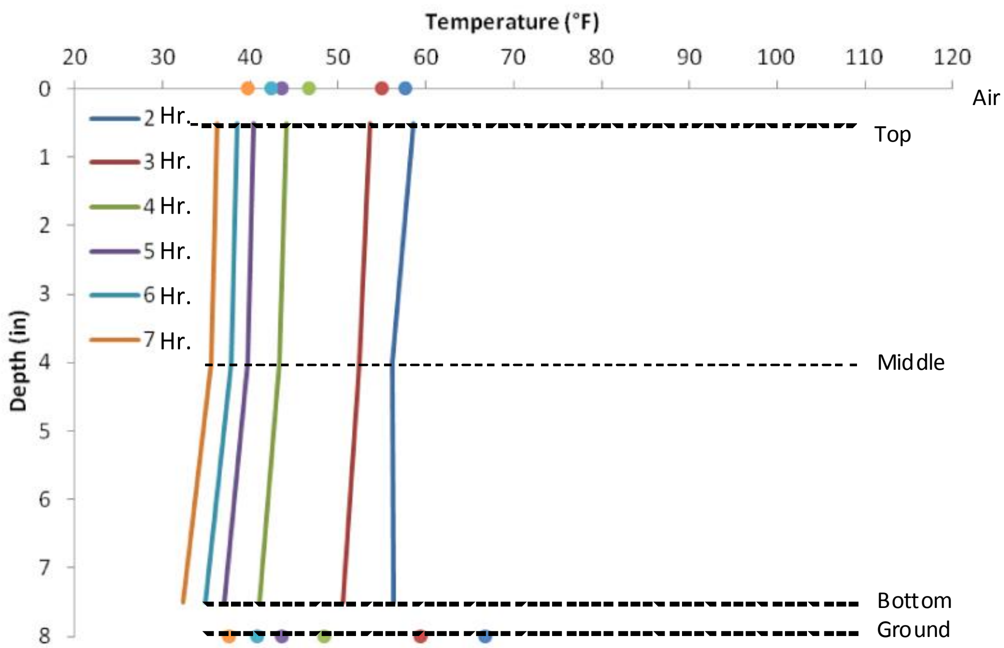

Figure 28: November 30, 2011 (winter) single layer curing compound temperature differentials

The curing compound tested was W.R. Meadows 1635 White Curing Compound. The surface of the October 4th curing compound sample was slightly warmer than sample that was cured with hourly misting on the same day. This is probably due to the reduced amount of evaporation at the samples surface. This isn't as noticeable when comparing the same two curing methods from the November 30th trial. It is believed that the cooler temperatures are what reduced surface temperatures on this trial.

Two layer of wet burlap

Figures 29, 30 and 31 present the trial data for samples cured with a single layer of wet burlap.

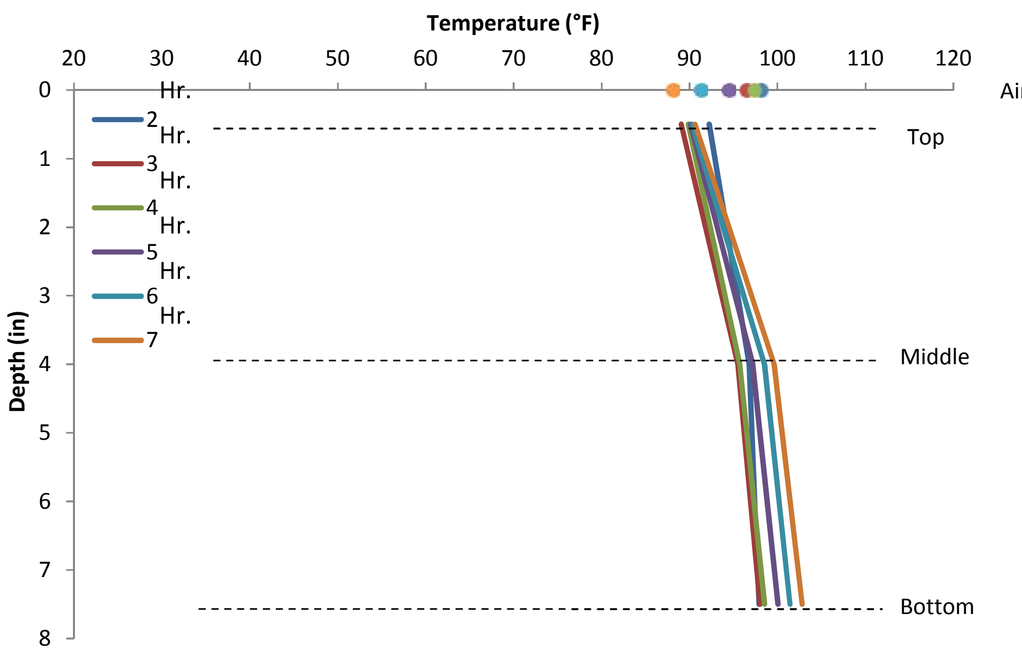

Figure 29: August 29, 2011 (summer) one layer of wet burlap temperature differentials

Wet burlap showed a much more constant temperature differential than all of the other previous curing methods investigated. The burlap likely acts as a covering that minimizes surface evaporation and also insulates the sample. The ability of this method to minimize the magnitude of the samples internal temperature gradient is superior to the other techniques.

One layer of wet burlap covered by one layer of clear plastic

Figures 30 and 31present data from curing with a single layer of wet burlap covered with plastic.

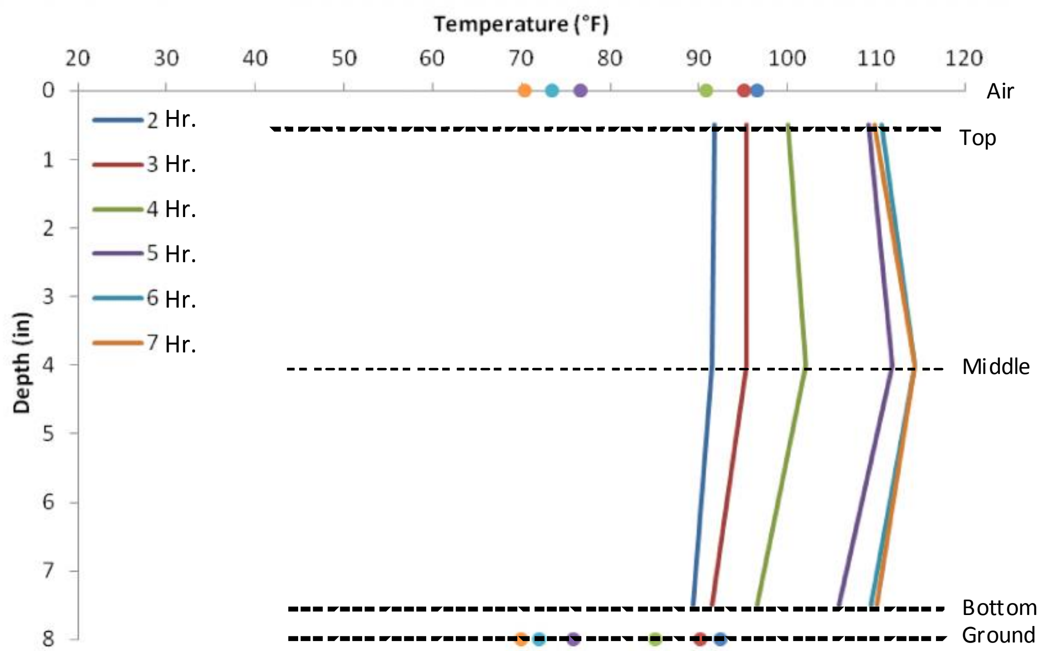

Figure 30: October 4, 2011 (fall) Temperature differentials for one layer of wet burlap and clear plastic

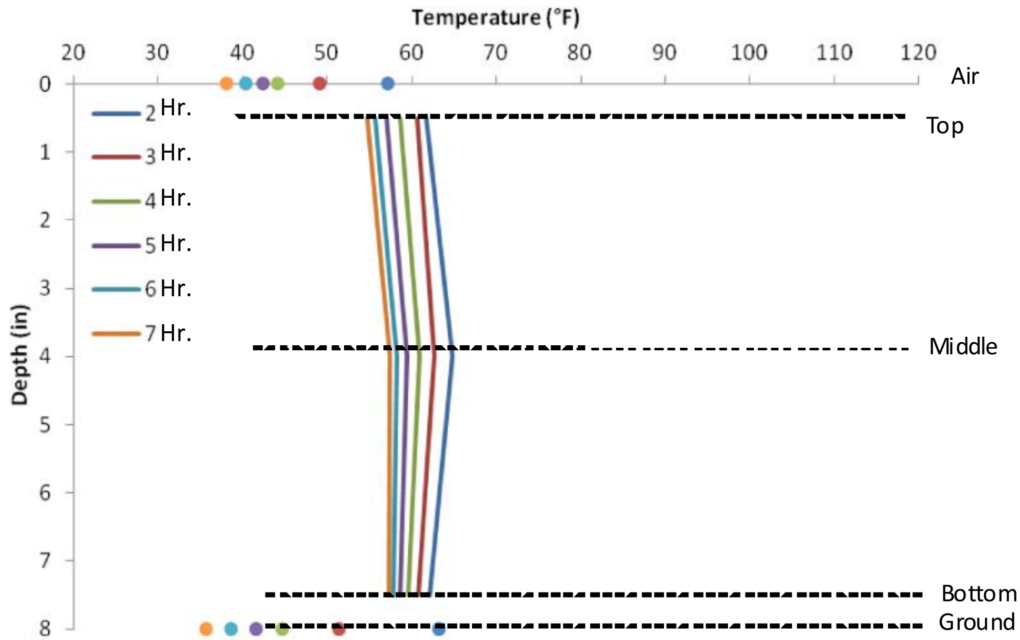

Figure 31: November 30, 2011 (winter) Temperature differentials for one layer of wet burlap and clear plastic

The use of wet burlap with a clear plastic covering showed consistent temperature differentials. The material at the top of the surface was hotter than the single layer of wet burlap samples. This suggests that the burlap and plastic combination insulate better by further reducing evaporation from the sample surface.

Result comparison

Table 3 shows the temperature differences of the top and bottom of the samples at two hour intervals after placement.

Table 3: Differences in temperature between the top and bottom of investigated samples at 3, 5, and 7 hours (negative denotes top cooler than bottom)

Curing Method	Investigation Date	Temperature Differences (°F)		
		3 (hr)	5 (hr)	7 (hr)
No Cure	8/29/2011	-0.5	-5.9	-5.1
	10/4/2011	5.0	***9.1***	***9.6***
	11/30/2011	3.0	2.9	2.2
Misting	10/4/2011	-2.4	***-8.3***	***-10.1***
	11/30/2011	***6.7***	***9.9***	***10.0***
Curing Compound	10/4/2011	1.7	-0.4	-5.8
	11/30/2011	3.1	3.3	3.8
One Layer Wet Burlap	8/29/2011	***-9***	***-10***	***-12.2***
One Layer Wet Burlap & One Layer Clear Plastic	10/4/2011	3.9	3.4	-0.3
	11/30/2011	-0.2	-1.6	-2.5

The samples that used a curing compound and one layer of burlap and clear plastic had the lowest temperature differentials of the samples investigated. The sample that used a single layer of wet burlap showed the highest temperature differential. This is likely due to the evaporation from the surface of the wet burlap.

The samples that were misted hourly and the no cure samples, showed similar trends to the single layer of spray on white curing compound.

Recommendations

After evaluating the results, the data suggests that temperature differentials as a result of curing method were found to be related to the properties of the curing method. These typically were related to the insulation properties of the material and the ability to minimize evaporation.

It is recommended that the curing method selected be capable of insulating the concrete. Curing concrete by means of misting or using curing compound does not insulate the concrete if it is important to have a uniform temperature gradient in the early ages of the concrete.

CHAPTER IV

CONCLUSION

This thesis is composed of two studies that investigated thermal effects in concrete pavements. The first study was a modified version of AASHTO T 336 which is the standard method for evaluating the coefficient of thermal expansion of concrete materials. The goal of this study was to successfully develop a modified method for evaluating CTE by providing more accurate results with real time data. The second study involved evaluating the performance of various concrete pavement curing methods to maintain the internal temperature gradient of concrete pavements. The goal of this study was to determine which, if any, of the tested curing methods could minimize the internal temperature gradient in a pavement and therefore reduce shrinkage of the concrete. Based on the data presented by the two investigations, the following conclusions were found:

Coefficient of thermal expansion

- The modified version of the CTE test method developed at Auburn with modifications by showed consistent and repeatable results. This is proven by the low coefficient of variation values.

- It appears that the modifications to the apparatus made to isolate the LVDT from varying temperatures was helpful and should be incorporated into future versions of this test.

- Measurement intervals at 150 second periods over multiple 24 hour intervals at varying temperatures should be strongly considered in future testing. This ensures that errors in testing are not made and that true sample equilibrium is reached for accurate CTE evaluation.

- Filtering of the deflection data prior to CTE evaluation is needed to ensure accurate evaluation of the sample. The interference seen during the continuous monitoring of the samples can greatly influence the calculated CTE of any given sample if it is not removed.

- The use of multiple frames is also suggested. Testing samples in different frames and comparing CTE values between the two also help minimize errors.

- Random changes in length recorded by the LVDT have been noticed during this testing. The source of these changes is unknown and would not have been observed if continuous measurement was not used. These errors occurred frequently and caused samples to have to be retested.

- In Oklahoma, a constant CTE value of 5.4 PPM/°F can be used in the MEPDG except for concretes using coarse aggregates from the Hartshorn and Sawyer aggregate pits.

Impact of curing methods on temperature

- Not curing a concrete is thought to be the worst curing situation. The samples that were not cured showed surface temperatures that fluctuated with change in environmental conditions.

- Using hourly misting as a curing method does not provide a noticeable difference in results compared to samples which were not cured. It is suspected that this is because the water evaporates quickly, and that there is not a large enough volume present to make a noticeable impact on the concrete placement.

- The use of spray on, white curing compounds also does not provide significant differences in temperature differentials when compared to misting and not curing at all. This is probably due to the lack of material present in the curing application. When properly applied, the curing compound can contain the moisture already present within the placement for hydration, it does not perform well as a temperature insulation material.

- Wet burlap showed the ability to insulate and maintain a improved temperature gradient throughout the sample depts. While it did not perform as well as the samples which were cured with wet burlap covered by clear plastic it remains a more plausible curing method for concrete pavements.

- While not the most plausible curing method for pavements, curing with wet burlap covered with a plastic membrane does provide the most insulation and constant temperature differentials of the methods tested.

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