EFFECT OF MOISTURE CONTENT ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

FINAL REPORT

By

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The purpose of this report is to discuss a study conducted on twenty separate mix designs of concrete and the effects of the aggregate type, moisture content, and temperature on the coefficient of thermal expansion(CTE). These results are to be used for the knowledge of proper choice of mix design for placement of concrete in structures dependent upon the moisture and temperature variations of the area.

There will be three separate types of tests performed to evaluate the effects on the concrete. The three tests are the AASHTO TP60-00 test, Danish T1-B method, and the Strain Gage method. An ANSYS program will be used for a Finite Element Analysis(FEA) to be performed for comparison of the capability of FEA in calculating CTE.

The results concluded in this report showed that humidity was not as great of a controlling factor as the aggregate type. The major controlling element was the aggregate due to the concrete's composition being approximately seventy percent aggregate and with the different mixtures porosities and accumulated moisture not having as great of an impact on the CTE.

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Abstract

The purpose of this report is to discuss a study conducted on twenty separate mix designs of concrete, which are typically used by MDOT, and the effects of the aggregate type and moisture content on the coefficient of thermal expansion (CTE). These results are to be used as a guide for the proper choice of mix.

In this study, three types of tests are performed to evaluate the effect of moisture content on CTE of concrete. The three tests are the AASHTO TP60-00 test, Danish T1-B method, and the Strain Gage method.

The results concluded in this report showed that humidity was not a major factor on CTE of concrete. The major controlling element was the aggregate type. This is due to the fact that, for the mix designs investigated, more than seventy percent of concrete volume is aggregate.

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CHAPTER 1

INTRODUCTION

The positions of atoms in matter changes with the variation of energy stored. As a result, matter usually expands when heated and contracts when cooled. This response to temperature change is called coefficient of thermal expansion (CTE). The CTE is a measure of a material's expansion or contraction with the change of environmental temperature. Due to the small length change, the CTE is usually expressed in micro strains per unit temperature change.

The aim of the CTE test is to determine the length/volume change of concrete due to the temperature change. Another usage of the CTE is to predict the potential deformation of a structure such as concrete pavement introduced by a gradient temperature. CTE is the one of the most important factors to be considered in the concrete pavement design. CTE can help engineers to better estimate the slab movement and to create some measures to prevent it from happening.

Although there exist typical values or ranges of CTE for common cement and concrete, CTE varies significantly depending on many factors such as type of aggregate, moisture condition, etc. Therefore, it is not proper to just use an average value as this may result in erroneous assumptions about the pavement's thermal response and possible distress. Five different sources of aggregates through Mississippi and four different combinations of cement blends lead to twenty different mixes that are typically encountered in Mississippi. Therefore, it is necessary to study the CTE of those twenty mixes used in Mississippi. Furthermore, environmental factors such as moisture vary significantly throughout Mississippi. For example, more rain falls in the far south close to Gulf of Mexico. Moisture condition effect on CTE may also need to be investigated.

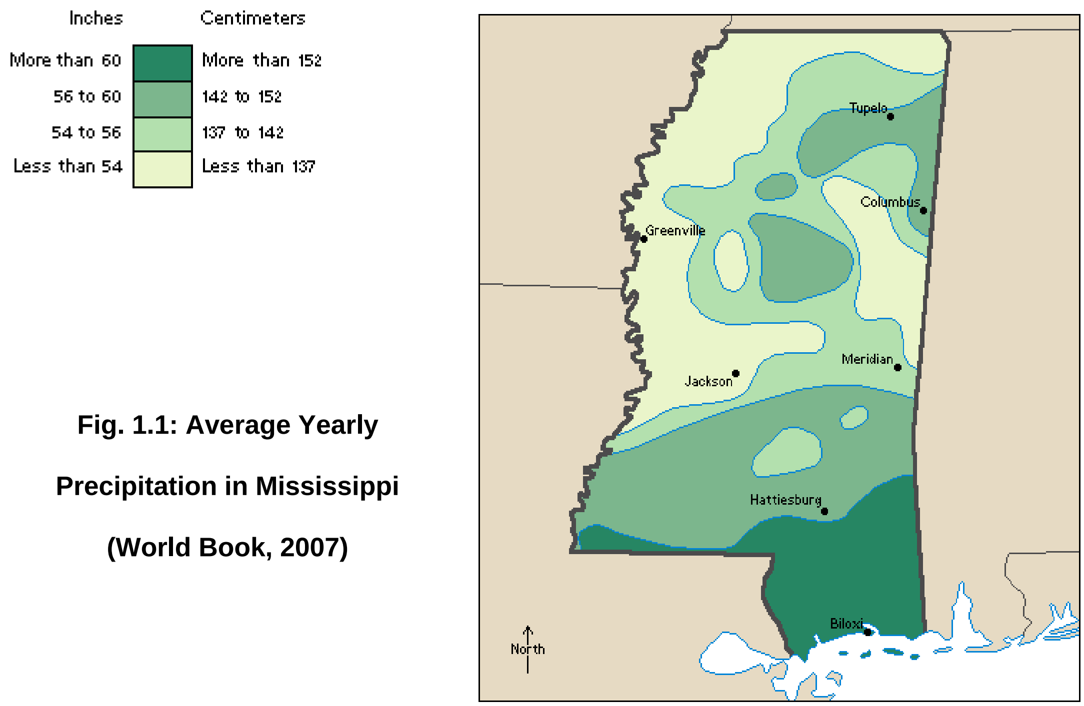


Fig. 1.1: Average Yearly Precipitation in Mississippi (World Book, 2007)

The purpose of this project is to conduct a study on CTE of twenty separate mix designs of concrete which are typically used by Mississippi Department of Transportation (MDOT), and to discover the effects aggregate type and moisture content have on CTE. These results are expected to be used as a guide for proper choice of mix.

Several test methods are being used to obtain CTE. Three of them are the AASHTO TP60-00 test, Danish T1-B method, and the Strain Gage method. In this study we used these three types of tests to evaluate the effect of moisture content on CTE of concrete; more specifically, CTE under relatively humidity at 0% (fully dried), at 25%, 50%, 75% and 100% (fully saturated) were evaluated.

CHAPTER 2

LITERATURE REVIEW

Portland Cement Concrete (PCC) is presently one of the main construction materials in the U.S. The consumption of concrete in the U.S is close to two tons per year for every U.S. resident. Concrete has emerged as the most widely used engineering material for several reasons: (1) It possesses excellent resistance to water; (2) Structural concrete elements can be easily formed into a variety of shapes and sizes; (3) Concrete is usually the cheapest and most readily available material on the job site; (4) Compared to most other engineering materials, the production of concrete requires considerably less energy input; and (5) Large amount of many industrial wastes can be recycled as substitute for various virgin material components in concrete (Mehta and Montelro, 1993). Because of these desirable features, concrete is still heavily being used in the pavement construction and rehabilitation throughout Mississippi today.

On the other hand, while designers of concrete structures have mostly been interested in the strength characterization of materials, for a variety of reasons they are also durability conscious. Concrete structures are inherently durable and usually, if properly designed and constructed, require low repair and maintenance. However, chemical reactions between concrete and the surrounding environment cannot be ignored. One of the main factors that affect both short-term and long-term properties of concrete is its thermal properties.

The U.S. Department of Transportation, Federal Highway Administration has developed a standard for the determining the value of CTE for many PCCs. The method they developed was adopted by AASHTO and named TP60-00. The method determines the CTE of cylindrical concrete specimens maintained in a saturated condition by measuring the length change of the specimen over a specified temperature range of 10 °C to 50 °C. Length measurements are made using Linear Volt Displacement Transducers (LVDT), with corrections made for the contraction of the test frame. AASHTO TP60-00 has been by far the most reliable method to determine the CTE of concrete. However, it has its disadvantages and limitations according to Moon Won (Won M, 2005) from the University of Texas at Austin. Won claims that the test accuracy and reliability depend on the accuracy and stability of the displacement readings, the tolerance between two successive CTE values of less than 0.5 microstrain/^{o}C is not small enough; the displacements at 50^{o}F and 122^{o}F are not stable. Won improved the accepted AASHTO TP60-00 standard by introducing regression analysis of temperature and displacement measurements (Won M, 2005). He also investigated the influence of rate of heating and cooling, age and specimen size on CTE, only to find out that they have negligible effects. Another method for determining the CTE of concrete is the Strain Gagging Technique. In this method a strain gage is applied to a specimen and temperature and humidity are varied and measurements are taken to calculate the CTE. Lastly the Danish have developed a method of calculating the CTE of concrete called the T1-B method. It consists of prisms 100 mm x 100 mm x 400 mm cast with disks placed on the side and a record of length changes taken with variations in temperature from 5 °C to 30 °C.

Another test method for coefficient of linear thermal expansion of concrete is designation CRD-C 39-81 or Strain Gage method (USACE, 1981) from US Army

Corps of Engineers which was issued in June 1981. This test method is simply to use a horizontal length comparator to measure the difference of the length readings at 40 ± 2^{o}F and 140 ± 2^{o}F in a specific moisture condition since CTE is a minimum when saturated or oven dried and a maximum at about 70% saturated.

The coefficient of thermal expansion of typical aggregate is 3 to 7 μ/°F and 6 to 11.5 μ/°F for hydrated cement paste (www.fhwa.dot.gov/pavement/pccp/thermal.cfm). The higher the coefficient of aggregate, the higher the CTE of concrete.

Table 2.1: Effect of Aggregate Type on Coefficient of Thermal Expansion of Concrete (Davis, 1930)

Aggregate Type (from one source)	Coefficient of Expansion, millionths per ^{o}C
Quartz	11.9
Sandstone	11.7
Gravel	10.8
Granite	9.5
Basalt	8.6
Limestone	6.8

The influence of hydrated cement paste on CTE is determined by moisture condition. When the specimen is in a dry or saturated condition, the CTE of the paste is lower than in a partially saturated condition. This is because the CTE of paste includes the movement of swelling pressure. When in the above two extreme conditions, there is no decrease in the capillary tension of water held by the paste, and thus causes no swelling. When heating the saturated specimen, the moisture diffusion from gel to capillary pores is partially eliminated by contraction as the gel loses water. According to Naville (1973), it was reported that for young paste CTE reaches the maximum when the relatively humidity is about 70% (Fig 2.1). Neville also claimed that concrete should also follow a similar trend.

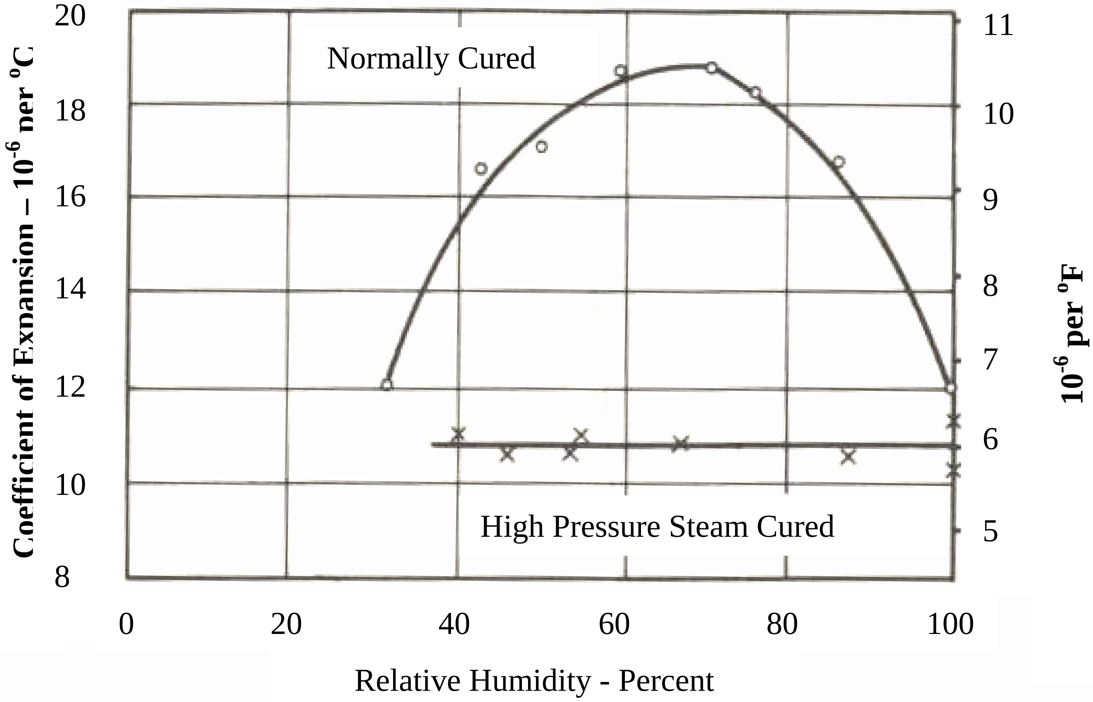


Fig. 2.1: Relation Between Relative Humidity and the Linear Coefficient of Thermal Expansion of Neat Cement Paste (Neville, 1973)

Some other factors may have an influence on CTE. Researchers from South Korea investigated the influencing factors for CTE of concrete (Yang, et al., 2003). They studied six different aggregate types, specimen shape (prism and cylinder), cycles of heating and cooling, and measurement types (dilatometer and strain gauges). They concluded that (1) CTE is dependent on different coarse aggregates; (2) the prism concrete specimen produced almost the same values of CTE under cycles of heating and cooling; (3) Specimen shapes are main affecting factors on CTE of concrete; and (4) CTE value obtained by cylinder specimen is lower than the prism specimen. The CTE value obtained by AASHTO is close to that obtained from PML strain gages. The use of fly ash reduces CTE according to Choketaweekarn and Tangtermsrikul (Choketaweekarn and Tangtermsrikul, 2006).

The CTE of Portland Cement Concrete (PCC) ranges from about 8 to 12 microstrains/°C. The table below shows the typical range of coefficient of thermal expansion released by US Department of Transportation Federal, Highway Administration. Since more than half of the concrete volume is coarse aggregate, the major factor influencing the CTE of concrete appears to be the type of coarse aggregate. It has also been noted that concrete containing well-graded aggregates has higher CTE values than concrete containing gap-graded aggregates.

Table 2.2: Typical CTE Ranges for Common PCC Components (FHWA, 2007)

	Coefficient of Thermal Expansion	
	10^{-6}/°C	**10^{-6}/°F**
Aggregate		
Granite	7-9	4-5
Basalt	6-8	3.3-4.4
Limestone	6	3.3
Dolomite	7-10	4-5.5
Sandstone	11-12	6.1-6.7
Quartzite	11-13	6.1-7.2
Marble	4-7	2.2-4
Cement Paste (saturated)		
w/c = 0.4	18-20	10-11
w/c = 0.5	18-20	10-11
w/c = 0.6	18-20	10-11
Concrete	**7.4-13**	**4.1-7.3**
Steel	11-12	6.1-6.7

CTE is one of the most important factors considered in pavement design. The values listed in the above table are not universal. Accurate value must be obtained in a specific pavement design, or one cannot predict the potential movement induced by temperature change.

Properties of aggregates play a significant role in the performance of concrete. The coefficient of thermal expansion influences the value of the CTE of the concrete containing such aggregates. The higher the CTE of the aggregate the higher the CTE of the concrete, but this relationship also depends on the amount of such aggregate in the mix proportions. It has been suggested that if the coefficients of the aggregate and the cement paste differ too much, a large change in the temperature may induce a break in their bond. This is because the aggregate composes 70-75 percent of the total solids volume of the mixture.

The CTE of concrete is related to the volumetric change that hardened concrete undergoes as a result of temperature change. The influence of the moisture condition also applies to the CTE of the concrete causing two movements, the CTE of the aggregate and the swelling pressure. No swelling is possible, however, when the specimen is dry, containing no water, or when totally saturated. This results in the partially saturated specimens having a higher CTE than those of the two extremes of dry and fully saturated. When the paste is self-desiccated the coefficient is higher because there is not enough water for the free exchange of moisture to occur between capillary and gel pores after the temperature changes.

Internal relative humidity is important to shrinkage and thermal stress development. A method of measuring the relative humidity's (RH) was studied by researchers at the University of Illinois at Urbana-Champaign (Graskey Z. C., and Lange D. A.,2007). Early methods of measuring RH were developed in 1930 and conducted in 1940. These early probes included mechanical, resistive, and capacitive methods. Capacitive probes still remain today a popular instrument for measuring RH inside concrete due to its cheap affordability and ease of operation. However capacitance probes can be slow to stabilize and can take up to 24 hours to obtain an accurate measurement. Technological advances, though, have led to more accurate and long-term stabile instruments. The development of a small capacitance sensor capable of embedment in concrete allows for measurement to begin at the time of casting. It is relatively cheap and can be left in position and more than one sensor can be placed at a time. A study done by the University of Illinois showed that encasing these sensors in a Gore-Tex pocket allowed the sensor to be capable of embedment in concrete. The Gore-Tex allowed for rapid vapor transmission while preventing the penetration of liquid moisture and ions that could cause errors in measurement. These small sensors could then be connected to a computer and could digitally transmit data to a data logger. The accuracy of the sensors as reported by the manufacturer was +/-2% RH at 10% to 90% humidity and up to +/-4% at 100% RH. The system was validated using saturated salt solutions and through measurements taken from sensors embedded in mortar.

Many design manuals for highway construction have recommended CTE values for the design of highways structures. AASHTO recommends a CTE of 11 parts per million per °C. The AASHTO recommendation does not take into account the variations in different local materials which vary between every region. It is obvious that the CTE of a concrete mix is dependent on the material factors such as aggregate, moisture, cement paste, and environmental conditions such as temperature fluctuations. Therefore, it is necessary for design to determine the CTE of concretes consisting of local materials. Udeme J. Ndon and K. L. Bergeson (Udeme et al., 1995), both members of the American Society of Civil Engineers, completed studies on different aggregates local to the state of Iowa. To test the CTE of concretes in their area they obtained two cores from two bridges 0.1 m in diameter and ranging in heights of 0.25 to 0.33 m. Thermal expansion tests were conducted in an environmental chamber capable of controlling both temperature and humidity and equipped with a data-acquisition system. Results were obtained under three different moisture conditions: dried in air, dried in oven, and water saturated. Each core was placed inside the environmental chamber and heated to 60 °C or cooled to -14 °C. This was accomplished by circulating methanol from a constant temperature bath through a coil around each core. Once the results were obtained, they were compared to those of AASHTO. Results obtained from these tests were in close agreement with those of AASHTO and were the same or less than the suggested 11 ppm per °C.

A study by Eyad Masad, Ramzi Taha, and Balasingam Muhunthan (Masad, et al., 1996) involved a finite element analysis of temperature effects on plain-jointed concrete pavements. They classified temperature stresses into two types, curling stresses and thermal-expansion stresses for their analysis. ABAQUS software was used to measure the finite element analysis of the pavement response. The first model performed studies on the effect of superposition of curling and thermal-expansion stresses and addressed the uniform temperature change on joint openings. The temperature values were introduced to the model using a FORTRAN subroutine available with the software package. The subroutine had the advantage of changing the temperature loading as a function of time and depth of the slab. For solid elements only one temperature value was needed at each node. Results were compared to calculations obtained using KENSLABS, ILLI-SLAB, and JSLAB. Masad, Taha, and Muhunthan (Masad, et al., 1996) concluded that the best results were obtained using the computer program JSLAB. Their test focused more on the basis of the curling stresses, but their method could still be applied to the CTE element of the experiment.

In this project, we compare the results of CTE obtained from the AASHTO TP60-00 standard test method developed by the TCCP team of FHWA to two more techniques: strain gaging and Danish Standard T1-B 101 (94). For the ASSHTO test, a 4x7 in concrete cylinder with both ends cut was submerged in a temperature controlled water bath. The temperature in the water bath changed from 50^0F to 122^0F and then to 50^0F again. In order to more accurately measure the length change, we introduced a new Iotech data collecting system which could obtain a series of readings automatically.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Until recently there has been no best CTE test method although the AASHTO CTE standard test method is a promising candidate. AASHTO TP60-00 and Danish T1-B are standard test methods while the Strain Gauge test is still under research. Many test methods, as stated in Chapter 1, have been proposed and been applied. Three different tests were performed to calculate the Coefficient of Thermal Expansion (CTE) of concrete for twenty different aforementioned mix designs that are commonly used in Mississippi. These three tests include:

- AASHTO TP60-00 test
- Danish T1-B method
- Strain Gage method

3.2 Materials and Mix designs

The materials used in this project are summarized in Tables 3.1 and 3.2. The types of aggregates and cements used are summarized in Table 3.3.

Table 3.1: Material Properties-Cementious Materials, Admixtures and Water

Material	Type	Source	Specific Gravity
Portland Cement	Type I	Local Building Store	3.15
Fly Ash	Type C	Boral Materials Technology-Fairfield, TX	2.65
Fly Ash	Type F	Boral materials Technology-Fairfield, TX	2.65
Slag		Holcim- Birmingham, Al	2.89
Admixtures	200 N and AE90	Degussa Admixtures	
Water		Tap Water	1
Aggregate		See table 3.2	

Table 3.2: Material Properties-Aggregate Used in This Study

Aggregate	Type	DOT #	Sp. Gr SSD	Absorption %	SSD Unit Weight, pcf
Light Weight Chert	Coarse	3-15-3	2.52	1.65	96
Crushed Limestone		# 67 Limestone	2.626	1.19	100
Kentucky Limestone		#57 Limestone	2.63	1.19	102
Dense Chert		Gravel #57	2.58	1.7	99
Small Maximum Size Chert		Gravel #69	2.49	3.4	98.1
Sand	Natural	3-15-42	2.61	0.56	-

Table 3.3: Types of Aggregates and Cements Used in the Study

Aggregate	Source	Cement
Light Weight Chert (Gravel 2-54-2)	Northern part of Mississippi (B&B Concrete, Oxford, MS)	Cement Type I
		Cement Type I+ FA Class F
		Cement Type I+ FA Class C
		Cement Type I+ Slag
Alabama Limestone (A-8-L)	B&B Concrete, Oxford, MS	Cement Type I
		Cement Type I+ FA Class F
		Cement Type I+ FA Class C
		Cement Type I+ Slag
Kentucky Limestone (Limestone #57)	(MMC)	Cement Type I
		Cement Type I+ FA Class F
		Cement Type I+ FA Class C
		Cement Type I+ Slag
Dense Chert (Gravel 57)	Central part of Mississippi Breen Brothers Gravel Co., Inc	Cement Type I
		Cement Type I+ FA Class F
		Cement Type I+ FA Class C
		Cement Type I+ Slag
Small Maximum Size Chert (Gravel #69) TXI 6-L-20	Southern part of Mississippi (Gulf Concrete, LLC)	Cement Type I
		Cement Type I+ FA Class F
		Cement Type I+ FA Class C
		Cement Type I+ Slag

Type I cement, a general purpose cement used widely in highway pavements and building construction, was used in this project.

The mix designs of the concrete are shown in Table 3.4

Table 3.4: Mix Design Used in This Study

ix	CA Type	Cement (lbs)	FA C	FA F	Slag	CA	Sand	Water	Admix 200N (oz)	Admix 90 (oz)
1	North MS Chert	548.00	-	-	-	1866.2	1226.1	219.2	16.4	3.0
2		411.00	-	137	-	1866.2	1205.0	219.2	16.4	3.0
3		411.00	137	-	-	1866.2	1205.0	219.2	16.4	3.0
4		274.00	-	-	274	1866.2	1205.9	219.2	16.4	3.0
5	AL Limestone	548.00	-	-	-	1944.0	1226.9	219.2	16.4	3.0
6		411.00	-	137	-	1944.0	1205.7	219.2	16.4	3.0
7		411.00	137	-	-	1944.0	1205.7	219.2	16.4	3.0
8		274.00	-	-	274	1944.0	1206.7	219.2	16.4	3.0
9	KY Limestone	548.00	-	-	-	1982.9	1188.7	219.2	16.4	3.0
10		411.00	-	137	-	1982.9	1167.5	219.2	16.4	3.0
11		411.00	137	-	-	1982.9	1167.5	219.2	16.4	3.0
12		274.00	-	-	274	1982.9	1168.5	219.2	16.4	3.0
13	Jackson Chert	548.00	-	-	-	1924.6	1134.6	219.2	16.4	3.0
14		411.00	-	137		1924.6	1113.5	219.2	16.4	3.0
15		411.00	137	-	-	1924.6	1113.5	219.2	16.4	3.0
16		274.00	-	-	274	1924.6	1114.5	219.2	16.4	3.0
17	Gulf Coast Washed chert	548.00	-	-	-	1907.1	1160.8	219.2	16.4	3.0
18		411.00	-	137	-	1907.1	1139.6	219.2	16.4	3.0
19		411.00	137	-	-	1907.1	1139.6	219.2	16.4	3.0
20		274.00	-	-	274	1907.1	1140.6	219.2	16.4	3.0

All specimens made for this project were prepared in a lab and allowed to cure for 28 days in a water bath before being removed and tested.

3.3 AASHTO TP60-00

3.3.1: Introduction of AASHTO TP60-00 CTE Test

This test was developed by the U.S. Department of Transportation Federal Highway Administration and was adopted by AASHTO and named TP60-00. The method determines the CTE of 4*7 cylindrical concrete specimens maintained in a saturated condition by measuring the length change of the specimen over a specified temperature range 50°F to 122°F. Length measurements were made using a spring loaded LVDT. In our study, we tested specimens under different levels of moisture conditions. Specimen preparation is described in Section 3.3.2. The schematic diagram for the device of AASHTO TP60-00 is shown in Figure 3.1.

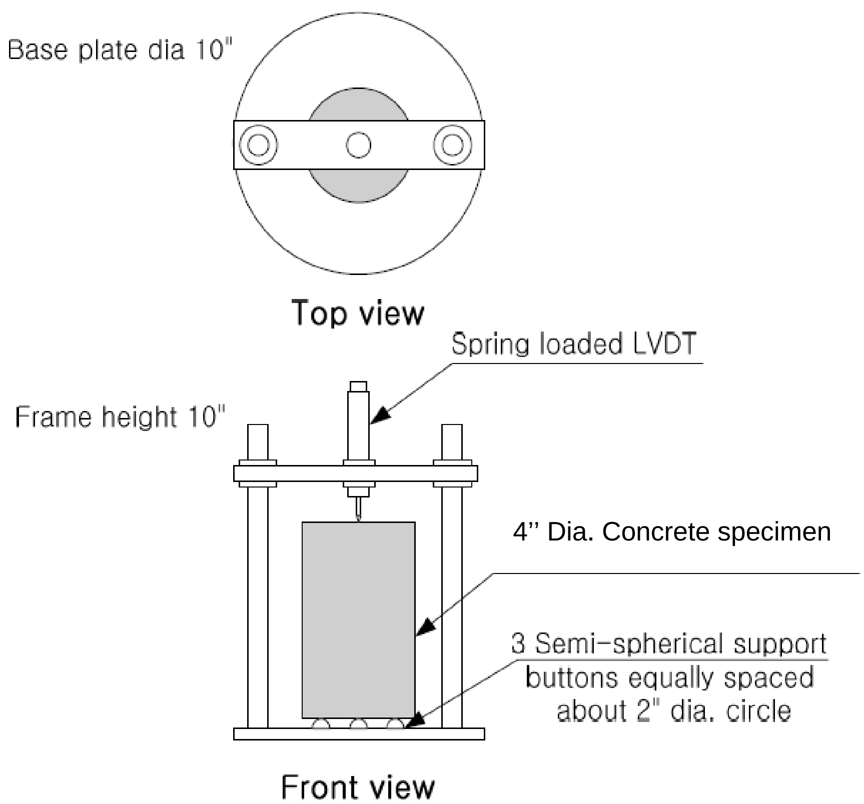
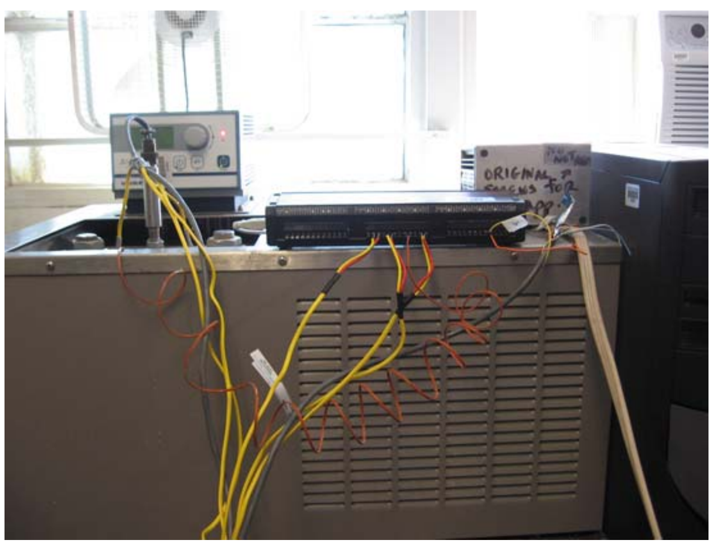
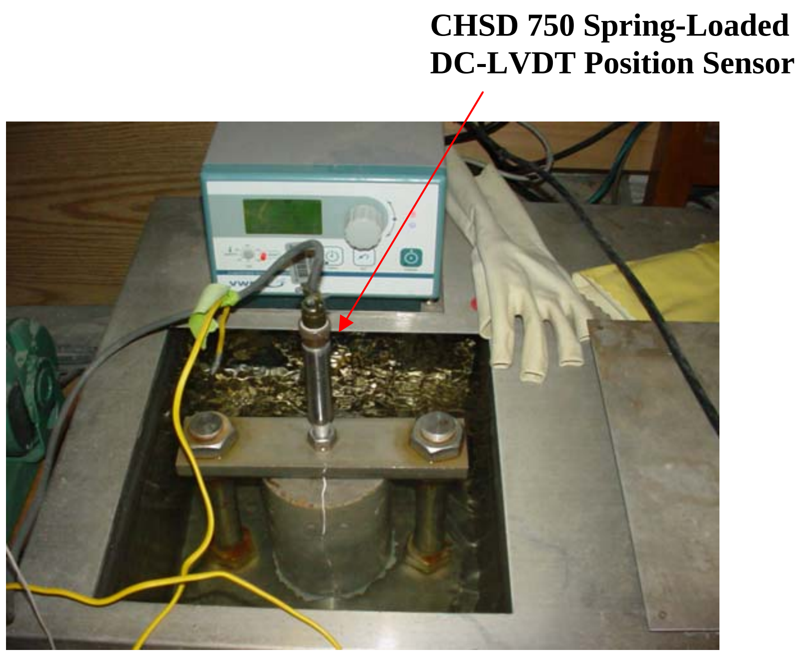


Fig. 3.1: Schematic Diagram for the Device of AASHTO TP60-00 (Yang S., et al, 2003)

A VWR programmable circulating bath (Fig.3.2a) was used to refrigerate and heat the water around the concrete specimen. This machine allowed us to control the temperature of the water from 50º F to 122 ºF. For each experiment, two thermocouples were used. One is inside the specimen and one is outside the specimen in the water bath. An Iotech Personal Daq. 3000 data acquisition system (Fig. 3.2c) allowed us to collect temperature measurements both in the water bath and inside the concrete specimen, and the displacement was measured by a GHSD 750 spring-loaded DC-LVDT position sensor (Fig. 3.2b), which was collected with the Iotech data collecting system. This position sensor consists of a spring-loaded shaft running in a precision sleeve bearing and connected to the core of a LVDT. Type K Thermocouples were used to measure the temperature of the water bath and type T was used to collect temperature information inside the specimens.

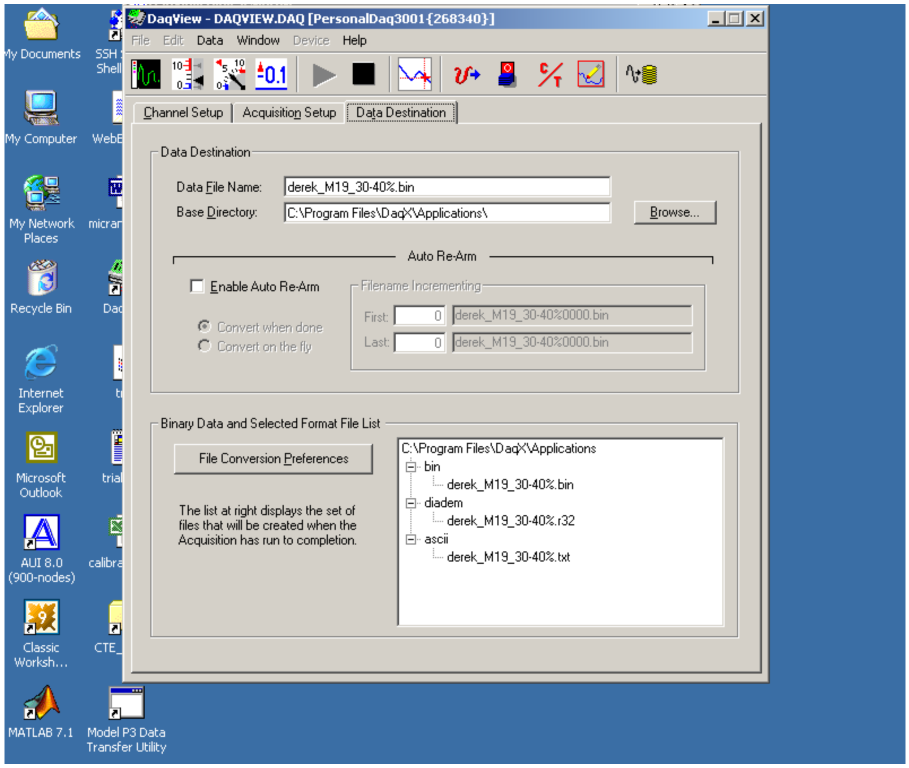


(a) VWR Programmable Circulating Water Bath



(b) Apparatus in Water Bath with Testing Specimen Seated and CHSD 750 Spring-Loaded DC-LVDT Position Sensor

(c) Iotech Personal Daq/3000 Data Collecting System



(d) Iotech Data Collecting System Software Daqview Interface

Fig 3.2: AASHTO TP60-00 CTE Test Setup (a)-(d)

All twenty mix designs were first placed inside the apparatus unsealed to allow for 100% saturation after transfer from the curing tank to the testing tank. Once each specimen had been tested at 100% humidity or fully saturated, the specimens' volumes were obtained so that their relative densities could be calculated. The specimens were then placed in an oven with reference disks from the original specimen that were cut from its ends until relative 0% saturation was obtained. Completely dry specimens were not actually obtained due to the makeup of the concrete. Weights of the specimens and their reference disks were taken until a consistent weight was obtained, at which time was taken as the dry weight. From these two measurements we can now obtain the density and calculate the predicted weight of each specimen at saturation levels of 25%, 50%, and 75% using its calculated volume and density. Specimens that were dried to a relative 0% humidity were then sealed using an epoxy coating to keep any moisture from reentering the specimen. Once this was completed the specimens could again be placed inside the AASHTO apparatus and testing was resumed to calculate the CTE of each specimen at 0% humidity. Cured specimens were placed inside an oven and weighed periodically until the calculated weights were reached for the humidity levels of 25%, 50%, and 75%. Once these calculated weights were reached these specimens, too, were sealed to prevent moisture loss or gain. They were set aside until testing could occur.

A reference cylinder was used to calibrate the machine for use in our experiment. This is because the expansion of the frame holding the LVDT device that measures elongation of the specimens must also be considered for accurate measurement of CTE. The reference cylinder is made of a material called Invar, which has a known coefficient of 1.5e-6 in/in per ºF. With this information we could then place the Invar cylinder into the apparatus and run it through our proposed cycle. Through this process we then measured the elongation of the Invar at the different water tables, which we could then calculate a coefficient of expansion. Taking the measured coefficient and applying it to our equations, we were able to calculate the expansion of the frame holding the LVDT since the measured was the combination of the coefficients of the two. These known coefficients could now be applied to all measurements of our specimens to calculate a more reliable CTE.

The LVDT we used in this study was a GCA/GCD Series Precision Gage Head, which allows for computer-obtained measurements and preset time intervals. The device allows for the placement of the specimen and the start of a programmed timeframe of temperature application to be run without constant supervision. Data was recorded on the computer and, once the program ended, a new specimen was placed and the process restarted. The device is also hermetically sealed to allow performance in conditions necessary for the experiment.

This method has been adopted by AASHTO, but a recent evaluation by Texas Department of Transportation noted that during the implementation of the policy, several researchers reported that the results could not be repeated or took too long to complete testing. This will be further evaluated in our experiment.

3.3.2 Specimen Preparation

- Step 1: Cast the required 4*8 cylinders with thermal couple type T embedded in the specimens, de-mold and submerge them in water tank for 28 days.

- Step 2: Take the specimens out from the water tank, and cut them from both ends by ½ in.

- Step 3: Those for 100% moisture condition are ready to test. For those with 0%, 25%, 50%, 75% moisture conditions, complete the calibration and have the weight vs. time calibration curve.

- Step 4: Calibration test. This test can be finished by the following procedures

a) Carefully cut 2-inch thick disks from each mix and submerge them in the water tank until they are fully saturated.

b) Take the disks out one by one, wipe away the water on the surface of the disks, measure and record the weight of the disk immediately using a digital scale, and put them in a temperature- controlled oven. This weight is referred to in this report as $CW_{100\%}$.

c) For the first 2 days, measure the weight of the specimens every 2 hours, in the following 2 days, every 4 hours, and then once a day. Usually it takes approximately 14 days for the disks to become fully dried and to show little weight variation.

d) Plot the calibration curve for each mix. A specimen calibration time vs. weight calibration curve can be seen in Figure 3.4.

e) Calculate the total weight of the moisture in the disk by subtracting the weight of the dried condition specimen $CW_{0\%}$ from the weight of the 100% moisture condition $CW_{100\%}$.

$$CW_m=CW_{100\%}-CW_{0\%} \tag{3.1}$$

also calculate the moisture in unit volume UW_m by:

$$UW_m= CW_m/CV_{disk} \tag{3.2}$$

Here $CW_{0\%}$ denotes the weight of the fully dried calibrated specimen, and $CW_{100\%}$ represents the weight of the fully saturated calibrated specimen. CW_m is the total moisture in the calibrated specimen. UW_m is the unit weight of the moisture in the calibrated disk and V is the volume of the specimen.

- Step 5: Determine 25%, 50% and 75% condition using the equations

$$W_{25\%}=W_{100\%}-0.75*UW_m*V \qquad (3.3)$$

$$W_{50\%}=W_{100\%}-0.50*UW_m*V \qquad (3.4)$$

$$W_{75\%}=W_{100\%}-0.25*UW_m*V \qquad (3.5)$$

Here $W_{x\%}$ denotes the weight of the testing specimen in x% moisture condition. V is the total volume of the test specimen.

- **Step 6:** Take the test specimens out of the water, take their volumes simply by measuring the volume difference of water, weigh them, then put them in oven until the weights reach the calculated values in desired moisture condition. Carefully seal each specimen using epoxy penetrating sealer. In this study, we did not account for the CTE of the epoxy sealer.

Fig.3.3: **Specimens Used in AASHTO TP60-00 Test**

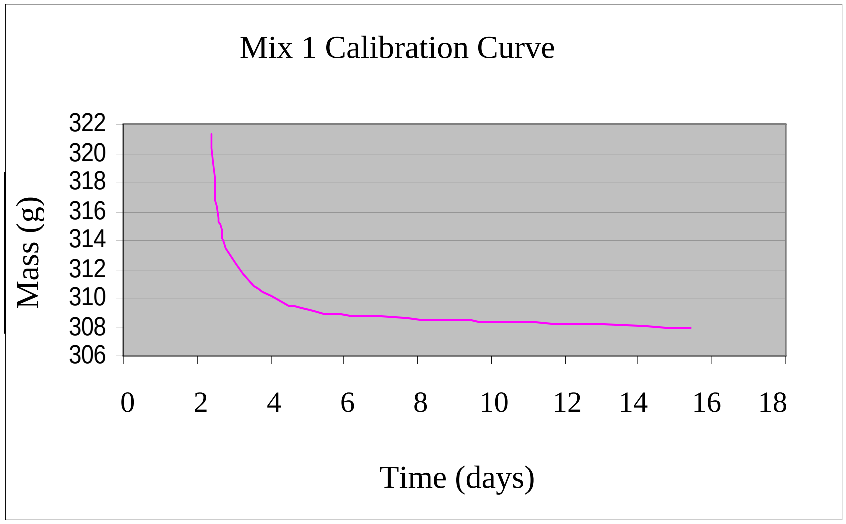


Fig. 3.4: **Specimen Calibration Curve**

3.3.3 AASHTO TP60-00 Test Procedure

1) Put the specimen in saturated limewater at 23 ± 2°C (73 ± 4°F) for at least 48 hours.

2) Prepare the Data acquisition system, programming the water bath. Set the temperature of the water bath from 50 ± 2°F, allowing the bath to remain at this temperature for at least 60 minutes. Increase the temperature to 122 ± 2°F, allowing it to remain for at least 60 minutes, and then changing it once again to 50 ± 2°F and sustaining this temperature for at least 60 minutes.

3) Place the measuring apparatus with LVDT position sensor attached in the water bath.

4) Measure the initial length of the specimen at room temperature, and place the specimen in the measuring apparatus, making sure that the lower end of the specimen is firmly seated against the three support balls, and that the LVDT tip is seated against the upper end of the test specimen.

5) Start the water bath and data acquisition system simultaneously.

3.3.4: AASHTO TP60-00 Test result Calculations

- CTE = length change/unit length/degree

1) According to the correction factor $C_{f,}$ calculate the length change of the measuring frame:

$$\Delta L_f = C_f * L_0 \tag{3.6}$$

2) Calculate the actual length change of the specimen by length change of the frame and the measured length change:

$$\Delta La = \Delta L_m + \Delta L_f \tag{3.7}$$

3) Calculate the expansion and contraction CTE by:

$$CTE = (\Delta L_a / L_0) / \Delta T \tag{3.8}$$

4) Obtain the test result: the average of the above two CTE values.

3.4 STRAIN GAGE METHOD

3.4.1 Introduction of Strain Gauge Test Method

Strain Gauge is not as widely used as the AASHTO and Danish T1-B methods. In this test method, strain gage is used to measure the length change with the change of temperature surrounding the test specimen. Compared to the other two test methods especially for the AASHTO test method, the strain gauge method is a relatively more tedious and time-consuming method.

3.4.2 Specimen Preparation

First, a specimen cylinder was taken from all twenty mix designs and three, one-inch thick disks, were cut from each cylinder. The mostly cement end was cut off before one inch disks were cut to ensure a more accurate average density between all three. Next the disks were set out for the surfaces to dry until ready for preparation. The disks were then wiped down with acetone which helped to absorb most of the water to allow application of the adhesive epoxy to be used to apply the strain gages. We used TML adhesives which are specially designed for bonding strain gages to test specimens. All specimens were also lightly sanded to clear surface debris and to make for a better contact surface. Once specimens were dried a small layer of polyester adhesive was applied to each side of the disks. When the epoxy dried it was sanded down to a very small thickness to ensure greater accuracy. P-Series gages type PL-60-11 purchased from Texas Measurement were applied to both sides of the disks using the same polyester adhesive. Once the bonding adhesive had dried a sealant coating of N-1 Chloroprene rubber was applied to seal the strain gages from moisture. The following photos demonstrate the process:

Fig. 3.5: Process of Strain Gage Placement and Measurement

To measure the humidity and temperature inside each disk, holes were drilled to ½ inch depth inside each specimen. Humidity sensors were then installed by a process using recommendations from the previously mentioned report by the University of Illinois. The humidity sensor used is a SENSERION-SHT71, four-pin type humidity and temperature sensor. The accuracy of the sensors as reported by the manufacturer was +/- 2% RH at 10% to 90% humidity and up to +/-4% at 100% RH. The process of installing these sensors included wrapping them in a Gor-Tex fabric and silicone tape to secure the Gor-tex around the sensor to prevent direct moisture contact which could damage the sensor, and a silicone sealant to prevent the measurement of the outside environment and removal from disk. The following figures show the sensor and its placement. The sensors are shown with the white silicone applied, sealing them into the disks only allowing the pins for connection to protrude.

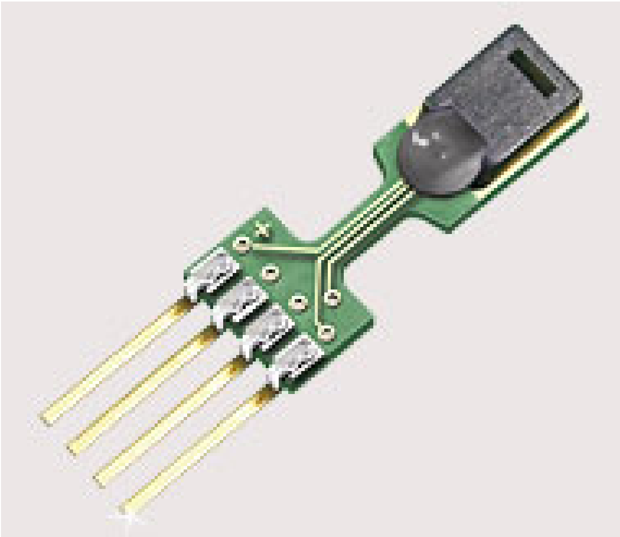


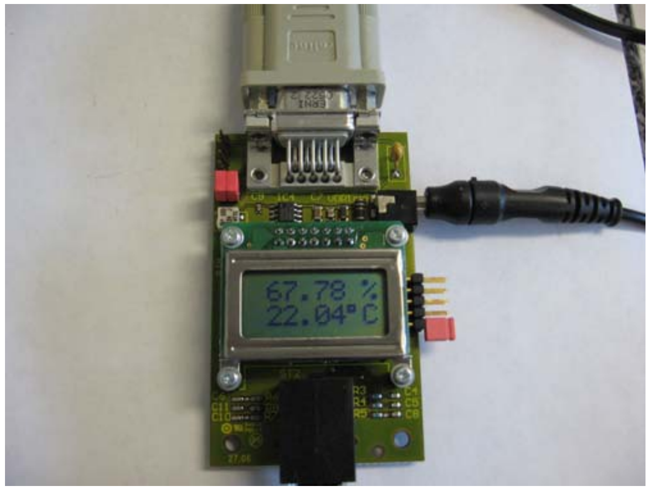
Fig. 3.6: SHT71 Humidity and Temperature Sensor

Fig. 3.7: SHT71 Sensor Under Silicone Coating After Placement

3.4.3 Test Procedure

Once all of the specimens were prepared they were placed in an oven to perform testing. Our original plan was to use a humidity and temperature-controlled environmental chamber, but mechanical problems forced us to resort to the use of an oven. Temperature and humidity measurements were still taken, however, and a secondary gage was placed inside the oven to record the oven humidity simultaneously. To insure 100% saturation, the disks were placed inside pans covered in water for test measurements. The test specimens were then dried in the oven until the humidity sensors gave readings at the appropriate levels of 0%, 25%, 50%, and 75%. The temperature was varied from approximately 25 ºC to between 50 ºC and 60 ºC.

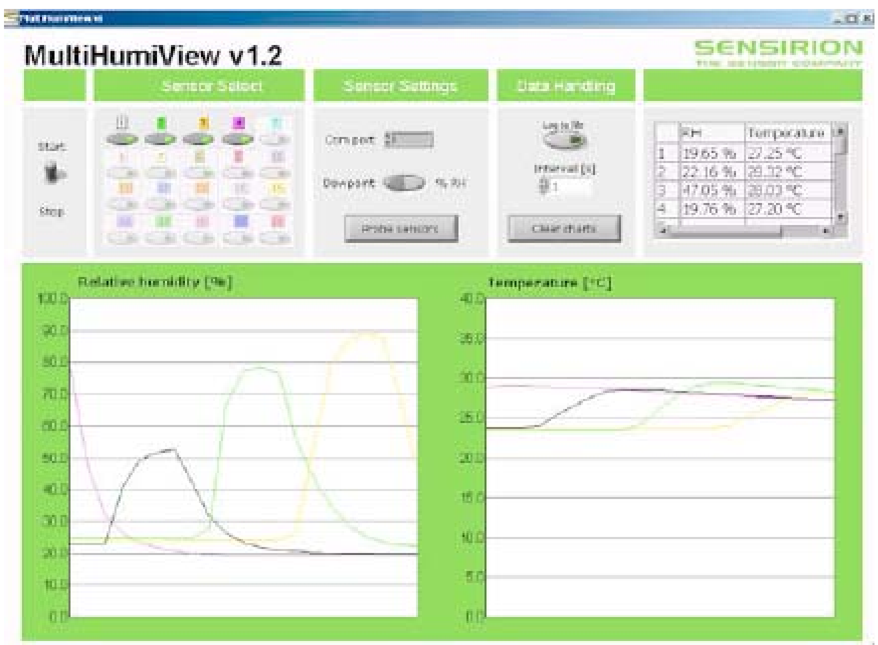
The humidity and temperature evaluation kit EK-H2 with software Humiview provided with the hardware manufactured by Sensirion sensor company was used to collect the relatively humidity information in a single testing specimen. With microprocessor board ASD11 and as shown in Figure 3.8a, the digital output signal of the SHTXY humidity sensor is recorded and transmitted to a PC by RS-232. In order to measure multiple RH's and temperatures at the same time, an EK-H3 logger was used. The EK-H3 Logger can read out a maximum of 20 SHT75 temperature and humidity sensors, shown in Figures 3.8b-d. The PL-60-11 strain gages were connected to a Vishay P3 Strain indicator and recorder, a portable instrument capable of simultaneously accepting four inputs from quarter-,half- and full-bridge strain-gage circuits, utilizing a large LCD display for the readout of setup information and acquired data as shown in Figure 3.9.



(a) **EK-H2 Logger Reads Out Only One SHT75 Temperature and Humidity Sensor**

(**b) EK-H3 Logger Reads Out a Maximum of Twenty SHT75 Temperature and Humidity Sensors**

(c) EK-H3 Back Plane with RS-232 Output and 5V Power Input

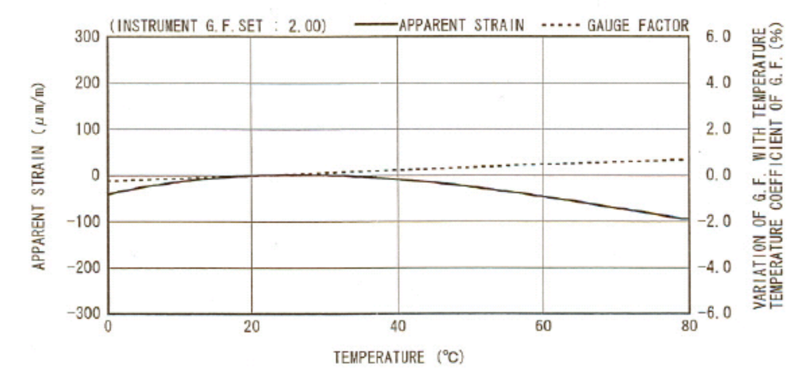


(d) Temperature and Relative Humidity Are Visualized on the Graph

Fig. 3.8: Relative Humidity and Temperature Measurement Setup

Fig. 3.9: Vishay P3 Strain Indicator and Recorder

The strain gages themselves have a varying CTE that is dependent upon temperature. This can is shown in Figure 3.10:



TML STRAIN GAUGE TEST DATA

GAUGE TYPE : PL-60-11	TESTED ON : SS 400
LOT NO. : P201711	COEFFICIENT OF THERMAL EXPANSION : 11.8 ×10⁻⁶/°C
GAUGE FACTOR : 2.09 ±1%	TEMPERATURE COEFFICIENT OF G.F. : +0.12±0.05 %/10°C
ADHESIVE : P-2	DATA NO. : C0039

THERMAL OUTPUT (ε app : APPARENT STRAIN)

$$\varepsilon_{app} = -3.97\times10^{1}+3.43\times T^{1}-7.84\times10^{-2}\times T^{2}+2.96\times10^{-4}\times T^{3}+4.94\times10^{-7}\times T^{4}\ (\mu m/m)$$

TOLERANCE : ±0.85 [(μm/m)/°C] , T : TEMPERATURE

Fig. 3.10: Strain Gauge Data Sheet

We summarize the procedures of the Strain Gage CTE test as:

-**Step 1:** Connect the humidity sensor corresponding with the number of the specimen. Press the probe sensor on the Mulitihumiview program. If the light illuminates then the sensor is properly attached. If not, rotate the connection 180 degrees and reconnect. Reprobe and it should now light up, indicating a correct attachment.

-**Step 2:** Wrap the sensor connection in Teflon tape to protect the wires and to ensure proper readings.

-**Step 3:** Place all of the specimens inside the chamber. Connect the strain gage wires to the P3 strain indicator and recorder. Once all of the gages have been connected, close the door and position the wires and never touch them again until all the duration of the test is complete. Touching and moving wires can alter results.

-**Step3:** Balance all of the gage wires. Take a reading of the humidity and temperature of the oven. Record the front and back reading for all gages. These are the initial readings.

-**Step 4:** Turn the oven on and set the dial to 150°F. Leave these specimens for 1.5 to 2 hours and then take a reading.

- **Step 5:** Set the dial to 175°F and leave the specimens for another 1.5 to 2 hours and then take another reading.

- **Step 6:** Set the dial to 200°F, leave the specimens for another 1.5 to 2 hours, and then take your last reading.

- **Step 7:** Once the above steps are completed, turn the oven off and place new specimens in the pan to run at 100% humidity. Leave the original specimens in the pan to dry while you run other specimens.
- **Step 8:** Continuously watch the humidity after running another sets of specimens. Once these other specimens have reached in the range of 75%, 50% and 25% you may reconnect their strain gages and humidity gages and test them at those humidities. Generally by leaving those specimens overnight at 200 degrees in the oven they will dry some 30% or less, depending on the mix design's porosity.
- **Step 9:** Compile and plot the data.

3.4.4 Test Results Calculation

To obtain the actual CTE, the following equation must be used:

$$\varepsilon = -3.97*10^{1} + 3.43*T^{1} - 7.84*10^{-2}*T^{2} + 2.96*10^{-4}*T^{3} + 4.94*10^{-7}*T^{4} \qquad (3.9)$$

$\varepsilon - apparent\ strain\ from\ gage = \varepsilon_1$

$T - temperature$

$$\varepsilon_2 = \varepsilon_1 + (\alpha_2 - \alpha_1) \qquad (3.10)$$

$where\ \ \varepsilon_2 - measured\ strain\ ,\ \alpha_2 - CTE\ Desired\ ,\ \alpha_1 - CTE\ of\ gage$

$reworking\ the\ equation\ to\ solve\ for\ \alpha_2$

$$yields: \quad \alpha_2 = \left[(\varepsilon_2 - \varepsilon_1)/\Delta T\right] + \alpha_1 \qquad (3.11)$$

Danish Method TI-B 101

3.5.1 Introduction of the Danish CTE Test

The Danish TI-B method is another choice to determine the coefficient of thermal expansion of concrete. This test method was established in 1994 by the

Danish Technological Institute. CTE is measured at three different temperatures range of 5 ºC to 30 ºC. The change in length, caused by the change in temperature in the range of 5 ºC to 30 ºC, is compared to the length at 20 ºC. The length between the measuring points on each test specimen is measured when the sealed specimen is kept in a constant temperature water bath for about two hours. The seal on each test specimen is quickly removed during the measurement.

3.5.2 Specimen Preparation

We cast three prisms with dimensions 100 mm x 100 mm x 400 mm for each mix design. Once these specimens had been removed from molds, they were placed in a curing tank for twenty-eight days. After curing they were removed and allowed to surface dry for the placement of measuring devices.

The device used to measure the CTE of each specimen is called a DEMEC gauge pictured below, which included the measuring device, placement bar, and calibrating bar.

Fig. 3.11: Demec Gauge, Reference Bar, and Calibration Bar

The Danish test requires a minimum accuracy of 10 e^{-6} [mm/mm]. The DEMEC gauge has an accuracy of +/- 5e^{-6} [mm/mm]. We obtained this gauge from the Mayes Group of Windsor England. The gauge measurement process uses reference disks which are placed on the prism as set by Danish standards. See Figure 3.12 below:

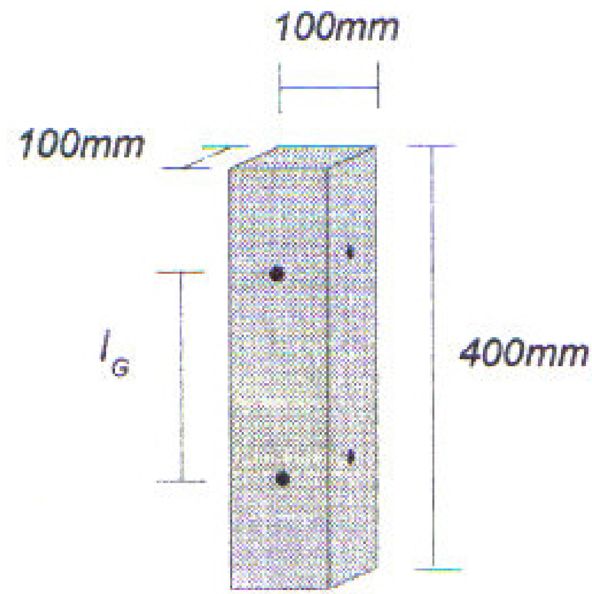


Fig. 3.12: Danish Specimen Dimensions

I_G is dependent upon the reference setting bar included with the gauge. The polyester adhesive used to secure the strain gages was also used to secure these disks. The disks are 6.3 mm diameter and flat in shape with a small indention in the middle to accommodate the placing of measuring points for the DEMEC gauge. The following pictures Figures 3.13 to 3.16 show the placement of disks and the measurement method of the prisms. Once the disks have been placed, the prisms were then submerged in the curing tank until testing could occur.

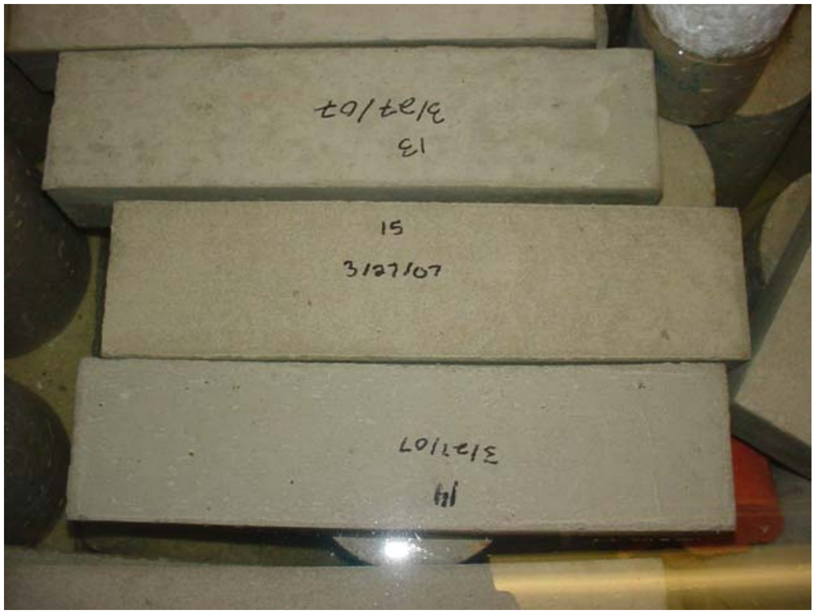


Fig. 3.13: Danish Test Specimens Curing in Water Bath

Fig. 3.14: Placing of Measurement Disks with Reference Bar

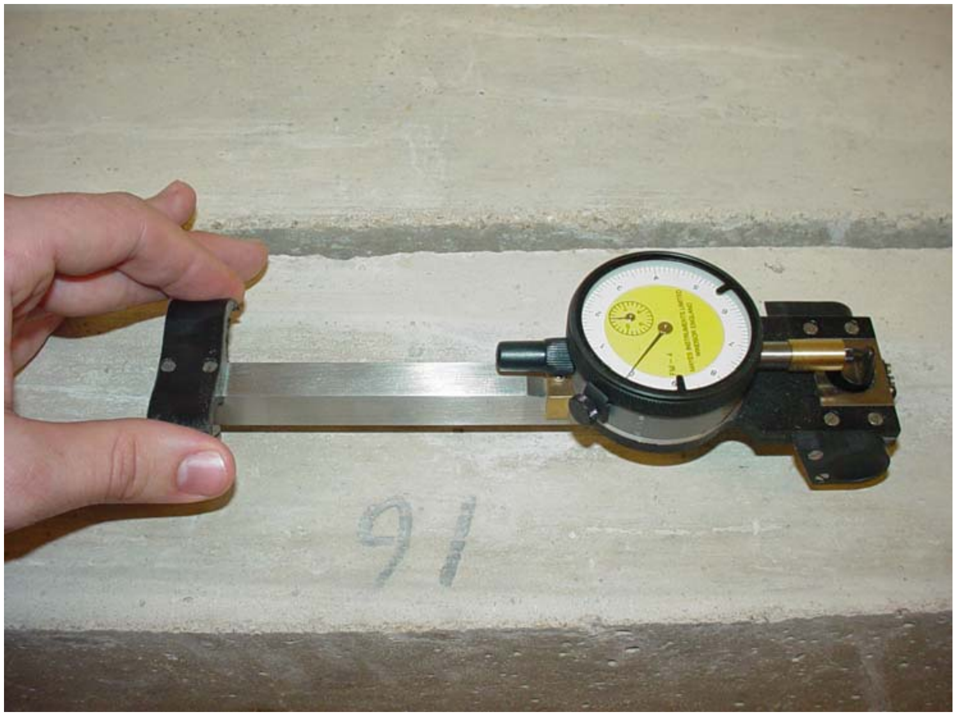


Fig. 3.15: Demec Gauge Placement on Measurement Points

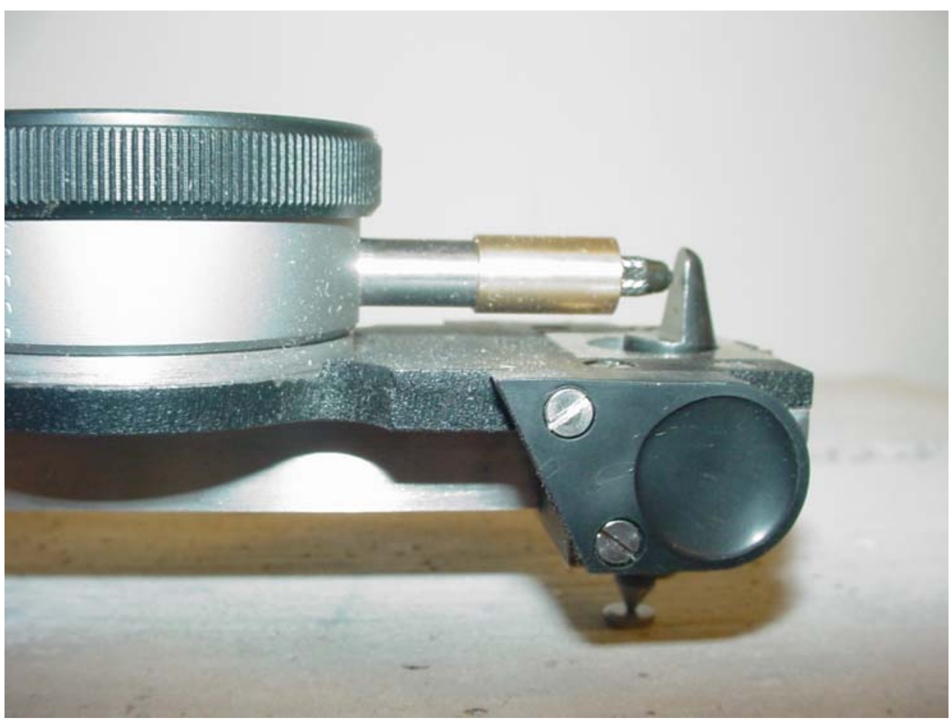


Fig. 3.16: Close View of Demec Gauge Measuring Points

3.5.3 Test Procedure

The process of the Danish test requires that the specimens be measured at three select temperatures, 5 ºC, 20 ºC, and 30 ºC. The process defined by the Danish states that there should be three storage tanks, each holding one of these required temperatures at equilibrium.

- **-Step 1:** After curing test specimens for 28 days, the specimens were removed from the water bath and either: (1) Tested immediately (Saturated), (2) Left to dry for two days before testing (Partially saturated), or (3) Left to dry for seven days before testing (Pseudo saturated).
- **-Step 2:** Begin by taking an initial measurement at room temperature of the specimens.
- **-Step 3:** Place the specimens inside plastic bags, place them in the water bath, and set the unit to 30ºC for about one to two hours for thermal balance to occur (that is when the inside and outside temperatures of the samples are the same).
- **-Step 4:** Once thermal balance occurs the specimen is pulled from the bath and a measurement is conducted. Now the prism is placed inside the plastic bag and the water bath is raised to 20°C.
- **-Step 5:** Once thermal equilibrium occurs the specimen is again removed and measurement of the disk length is again carried out. The prism is now returned to the plastic bag again and in the water bath until thermal equilibrium at 5ºC is reached.

-Step 6: Once this occurs the prism is again removed from the water bath and a final measurement is taken.

-Step 7: Once measurements are completed, the prisms are then stored in a room temperature bath in case future testing is necessary.

In our experiment, due to the high cost of equipment required to sustain three separate water baths at these temperatures, we decided to change the process somewhat. We purchased one Merlin M75 Recirculation Chiller pictured in Figure 3.17.

Fig. 3.17: Merlin M75 Chiller Water Temperature Control Unit

The device has the capability of controlling temperatures of a water bath in the range of -15 ºC to 40 ºC. So instead of using three tanks holding one each of equilibrium at 5, 20, and 30°C, we controlled the temperature and allowed the prisms to sit until equilibrium was reached. To speed up the testing time for an earlier completion date, the chiller was fabricated to be connected to a large cooler purchased from a retail store, allowing for ease of placement and removal, and for complete sealing of the water from the outside environment for more efficient temperature control. In doing this, we were able to test three specimens at time, thus cutting the testing time by a third of original estimates. Our process for testing the specimens was discussed in the above steps. The M75 was found to be adequate at heating and cooling while sustaining equilibrium, but to allow for a 5 ºC temperature the water bath had to be mixed with 50% glycol 50% distilled water solution. Once this occurred time for raising temperatures from lower temperatures increased, so it was decided to start at the higher temperature and then drop to the lower temperatures. The M75 was able to cool with relative ease with this solution then in place. The whole test procedure can be simplified as Figure 3.18:

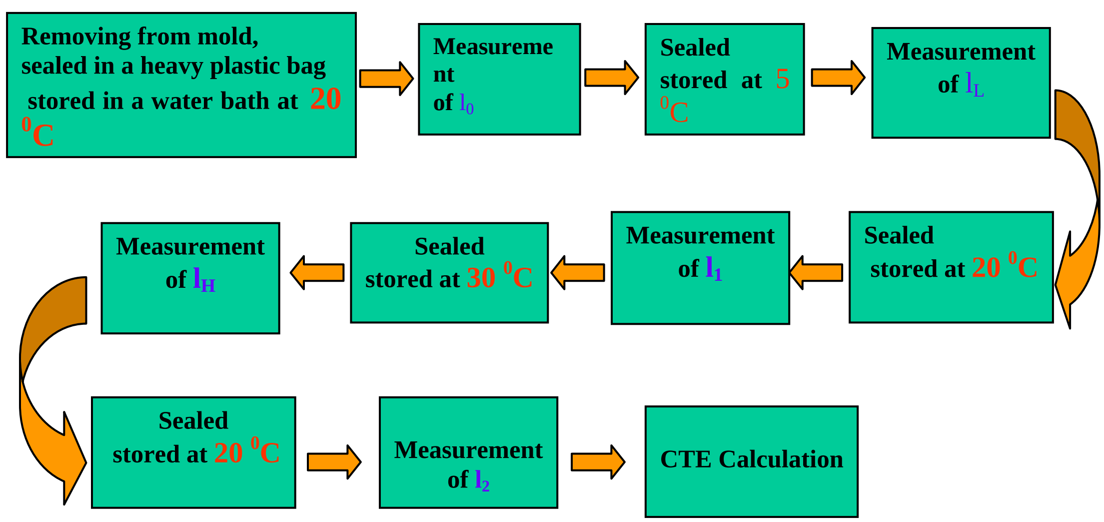


Fig. 3.18: Test Procedure of Danish TI-B CTE Test

3.5.4 Test Results Calculation

Calculating the CTE is then applied through the following equation:

$$Extension: increase\ in\ length\ from\ the\ original\ gauge\ length$$
$$Strain; extension\ \exp ressed\ in\ relation\ to\ the\ original\ gauge\ length$$
$$x = reading\ measured\ from\ DEMEC\ guage$$
$$Extension = 0.8 \cdot x \cdot 0.002$$
$$Strain = \frac{extension}{gauge\ length} \tag{3.12}$$

Once Strain has been calculated from these equations, they are then plotted using strain versus change in temperature. A trend line is then fitted to the graph from which we obtain our CTE.

Or, we can simply calculate CTE as:

$$\alpha = \frac{\Delta l}{l_0 \bullet \Delta T} \tag{3.13}$$

α- CTE

Δl - Corrected change in length

l_0 - actual measured length at 20^{o}C at the beginning of the test

ΔT - temperature difference at the measured lengths

$$\Delta l = l_H - l_L \tag{3.14}$$

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 AASHTO Test

The calculated results of the AASHTO method values for the CTE of all twenty mix designs and at corresponding humilities of 100%, 75%, 50%, and 0% are in the following Table 4.1. The results can also be seen in the following graphs with comparison to a mix's CTE with different humidities in Figures 4.1 through 4.8.

Table 4.1 Results of CTE's from AASHTO Test

Mix 1 Humidity %	Calculated CTE	Mix 2 Humidity %	Calculated CTE	Mix 3 Humidity %	Calculated CTE
100	8.1E-06	100	8.6E-06	100	5.8E-06
75	1.0E-05	75	1.1E-05	0	7.3E-06
0	8.9E-06	0	9.4E-06		
Mix 4 Humidity %	**Calculated CTE**	**Mix 5 Humidity %**	**Calculated CTE**	**Mix 6 Humidity %**	**Calculated CTE**
100	7.4E-06	100	5.5E-06	100	5.5E-06
75	8.6E-06	75	8.9E-06	75	6.7E-06
30	8.6E-06	0	8.1E-06	0	6.8E-06
Mix 7 Humidity %	**Calculated CTE**	**Mix 8 Humidity %**	**Calculated CTE**	**Mix 9 Humidity %**	**Calculated CTE**
100	6.1E-06	100	6.5E-06	100	6.4E-06
75	5.7E-06	0	7.7E-06	75	6.6E-06
0	6.6E-06			0	7.5E-06
Mix 10 Humidity %	**Calculated CTE**	**Mix 11 Humidity %**	**Calculated CTE**	**Mix 12 Humidity %**	**Calculated CTE**
100	5.6E-06	100	6.2E-06	100	6.6E-06
75	8.4E-06	75	5.8E-06	75	6.1E-06
0	6.8E-06	0	8.0E-06	0	7.1E-06
Mix 13 Humidity %	**Calculated CTE**	**Mix 14 Humidity %**	**Calculated CTE**	**Mix 15 Humidity %**	**Calculated CTE**
100	6.0E-06	100	7.9E-06	100	8.2E-06
75	9.7E-06	75	9.8E-06	0	9.3E-06
0	8.6E-06	0	9.6E-06		
Mix 16 Humidity %	**Calculated CTE**	**Mix 17 Humidity %**	**Calculated CTE**	**Mix 18 Humidity %**	**Calculated CTE**
100	8.0E-06	100	7.7E-06	100	6.6E-06
75	1.1E-05	0	9.1E-06	0	9.0E-06
0	9.6E-06				
Mix 19 Humidity %	**Calculated CTE**	**Mix 20 Humidity %**	**Calculated CTE**		
100	8.2E-06	100	7.5E-06		
75	1.2E-05	75	9.1E-06		
0	9.5E-06	0	9.9E-06		

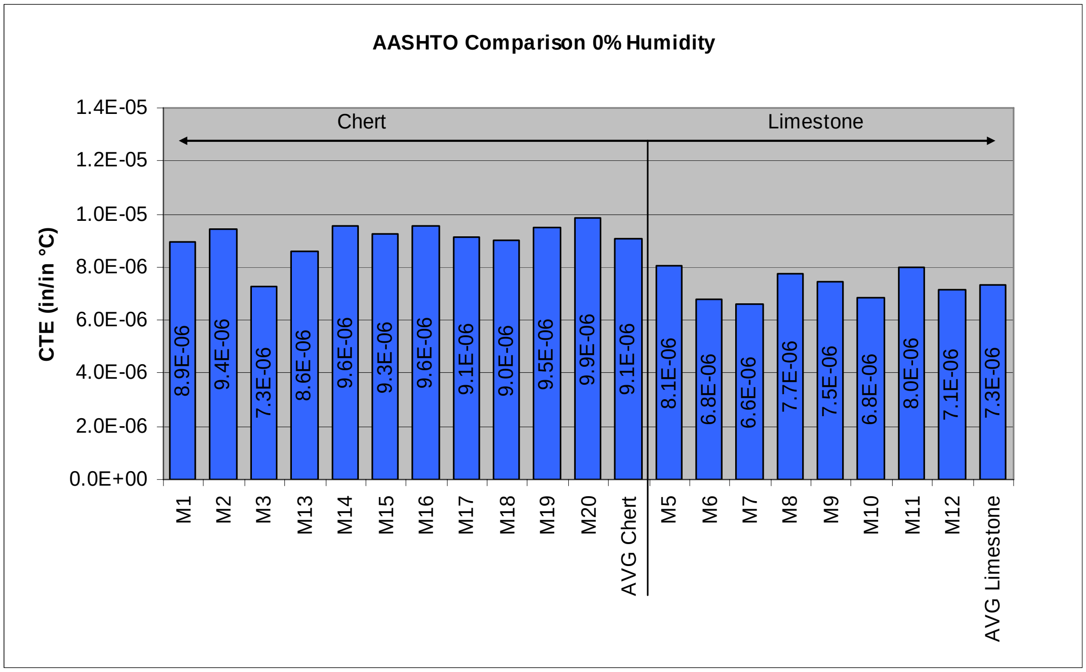


Fig. 4.1: AASHTO Comparison of Chert to Limestone at 0%

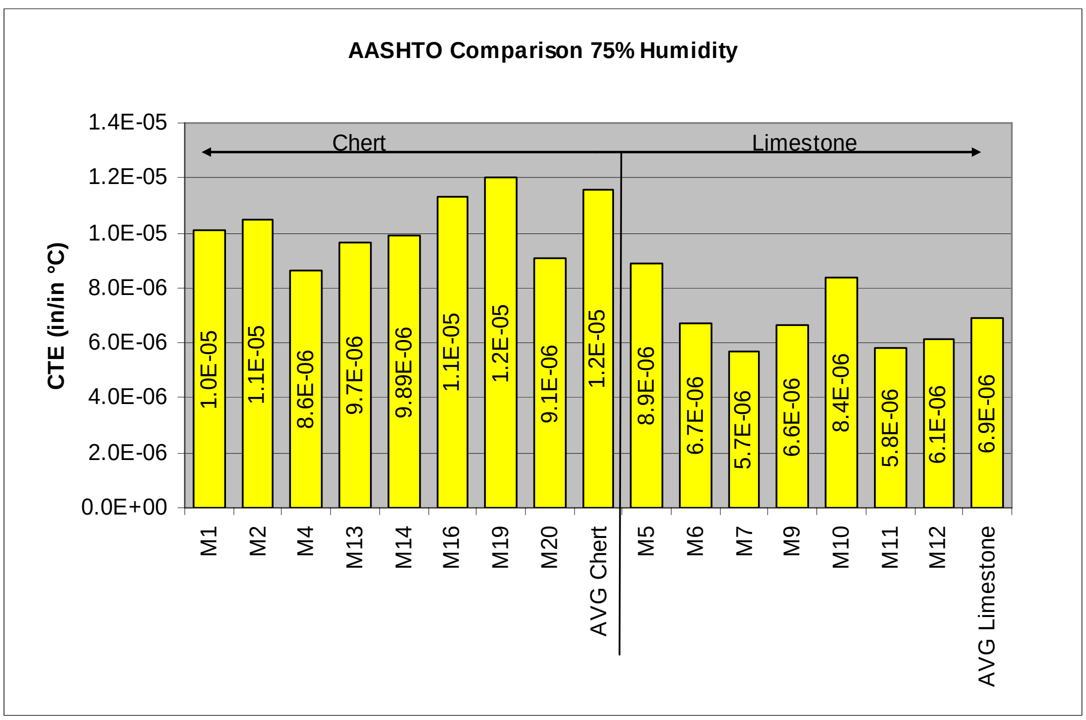


Fig. 4.2: AASHTO Comparison of Chert to Limestone at 75%

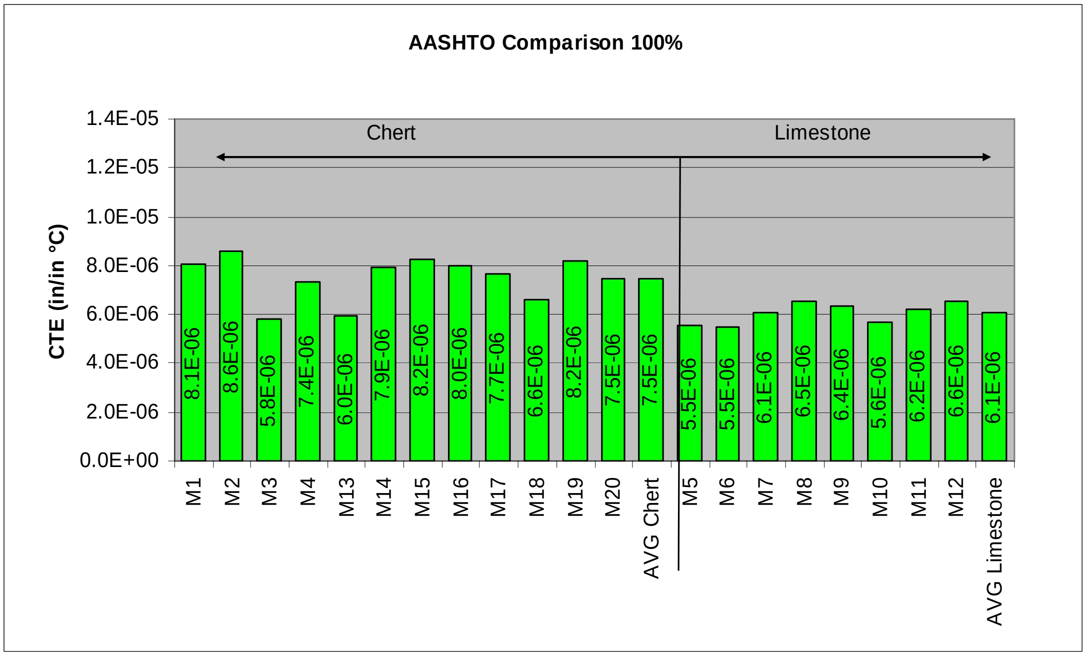


Fig. 4.3: AASHTO Comparison of Chert to Limestone at 100%

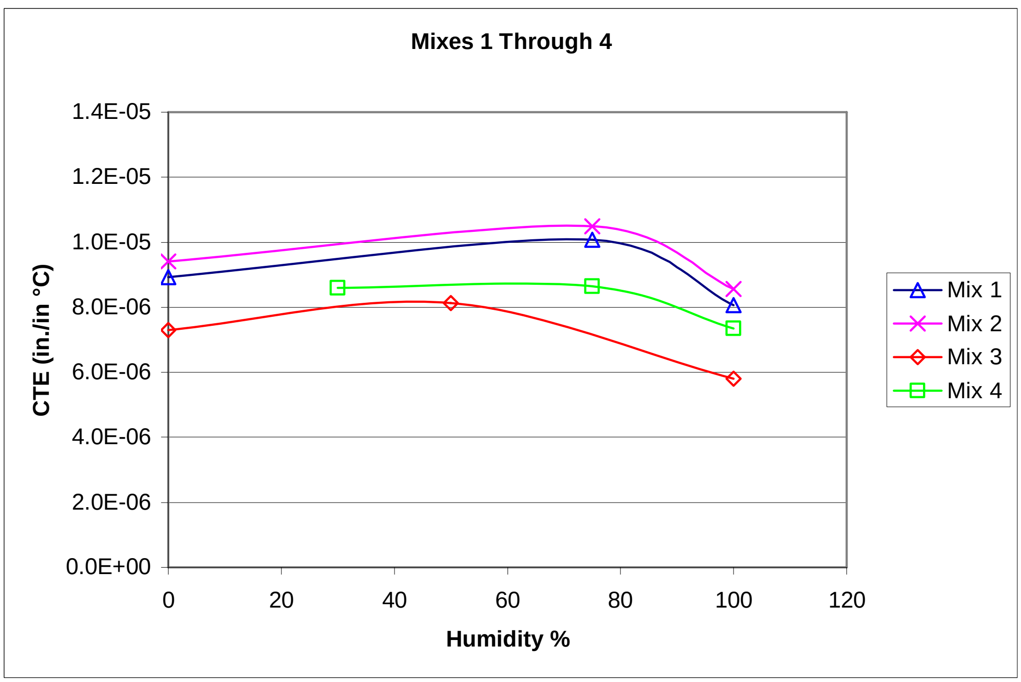


Fig. 4.4: AASHTO Mixes 1 Through 4 Results Plotted

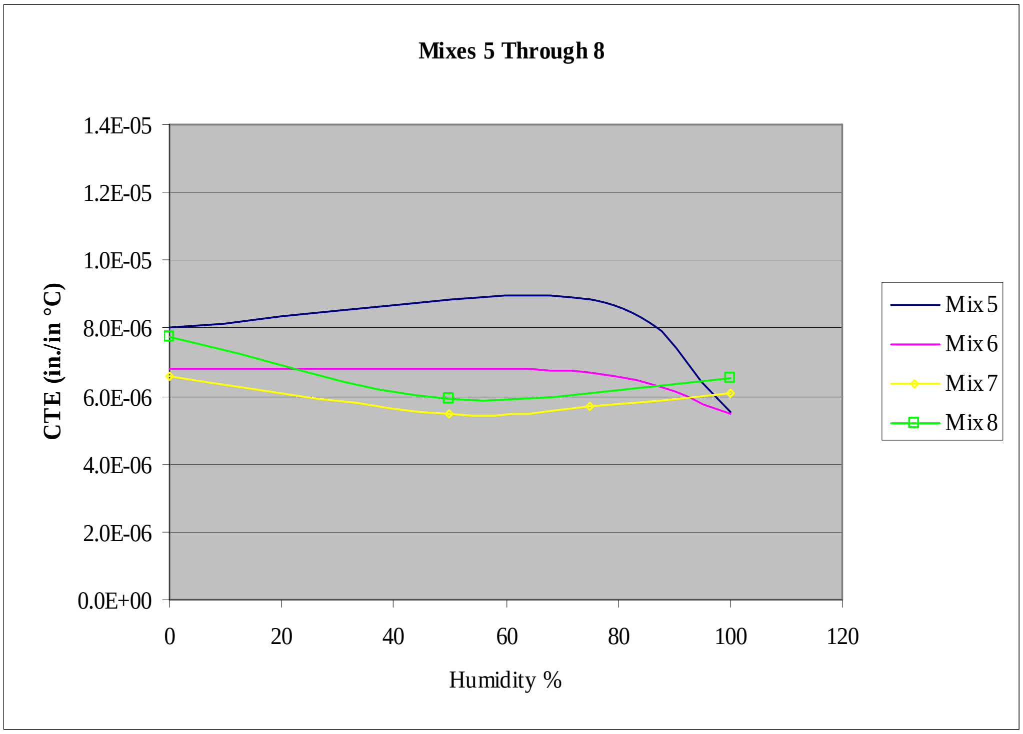


Fig. 4.5: AASHTO Mixes 5 Through 8 Results Plotted

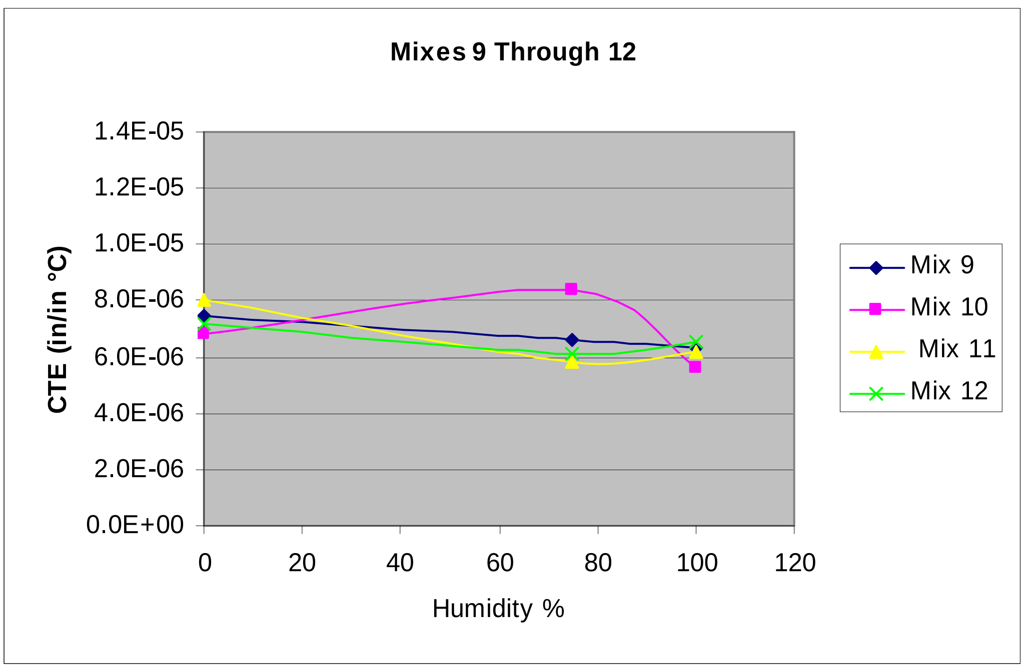


Fig. 4.6: AASHTO Mixes 9 Through 12 Results Plotted

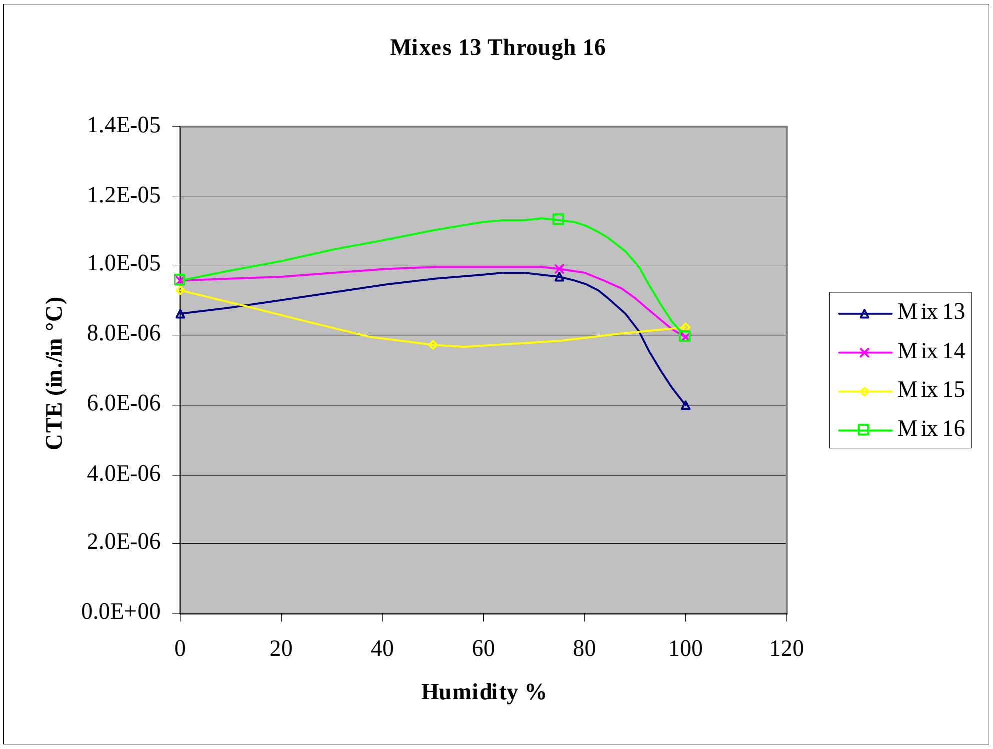


Fig. 4.7: AASHTO Mixes 13 Through 16 Results Plotted

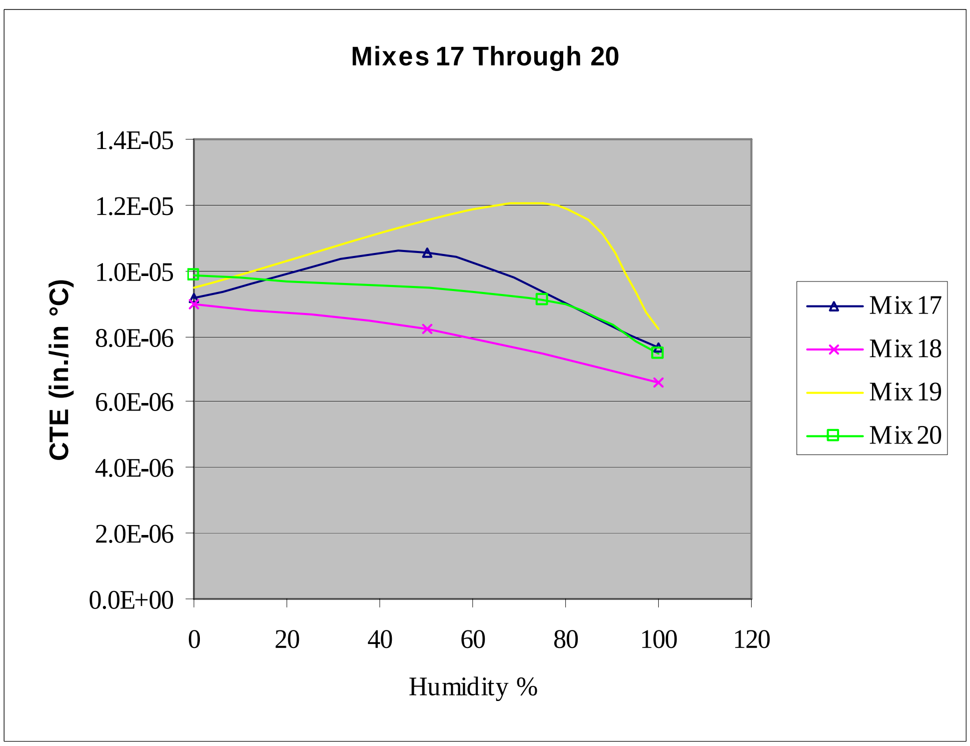


Fig. 4.8: AASHTO Mixes 17 Through 20 Results Plotted

As shown by Figures 4.1 through 4.4, all mixes, when compared, show the specimens with chert aggregates to have higher CTE values than those of limestone, except for Mix 3 and Mix 13 on different humidities. There may be some error in the specimens that may need to be investigated further. As demonstrated by Figures 4.5 through 4.9 there is not a common occurrence in deformation for all. Most of them did follow a curve which showed the minimum values being at 0% and 100% humidity and the maximum at around 70% humidity. Not all specimens followed this curve, however. Some specimens went in a downward curve. Some causes of this curve would be the placement of the LVDT point onto say an aggregate on the top end of one sample and onto the space of cementious material for another specimen. Also, some mixes had more than one specimen, so there may be an error due to data from comparing two separate specimens, with the difference due to the aggregate structure inside the specimen. Some further research may be needed to test these theories. Statistically, there was a maximum increase of 62% in the case of mix 13 and a maximum decrease of 4.25% for Mix 9 when compared between mixes with different saturations. The mean variation was 21.73% with a standard deviation of 18.62%.

4.2 Strain Gage Test

Table 4.2 reveals the results from using the Strain Gage test method.

Table 4.2 Results of CTE from Strain Gage Method

	Pseudo Dry CTE (E-06)		Partially Saturated CTE (E-06)		Saturated CTE (E-06)
Mix 1	14.76	Mix 1	14.94	Mix 1	14.51
Mix 2	14.57	Mix 2	15.20	Mix 2	15.46
Mix 3	15.14	Mix 3	15.39	Mix 3	15.55
Mix 4	10.50	Mix 4	16.01	Mix 4	15.34
Mix 13	15.40	Mix 13	15.37	Mix 13	15.65
Mix 14	14.85	Mix 14	16.28	Mix 14	15.36
Mix 15	15.10	Mix 15	15.18	Mix 15	16.16
Mix 16	14.63	Mix 16	14.95	Mix 16	14.92
Mix 17	14.37	Mix 17	15.13	Mix 17	14.71
Mix 18	15.38	Mix 18	15.71	Mix 18	15.55
Mix 19	14.82	Mix 20	15.92	Mix 19	14.98
Mix 20	15.13	Mix 7	11.95	Mix 20	14.50
Mix 7	10.32	Mix 9	13.10	Mix 7	12.45
Mix 9	10.26	Mix 10	12.93	Mix 9	12.54
Mix 10	12.16	Mix 11	10.15	Mix 10	11.22
Mix 11	10.34	Avg. Chert	15.46	Mix 11	12.85
Mix 12	10.43	Avg. Limestone	12.03	Mix 12	12.97
Avg. Chert	14.55			Avg. Chert	15.22
Avg. Limestone	10.70			Avg. Limestone	12.41

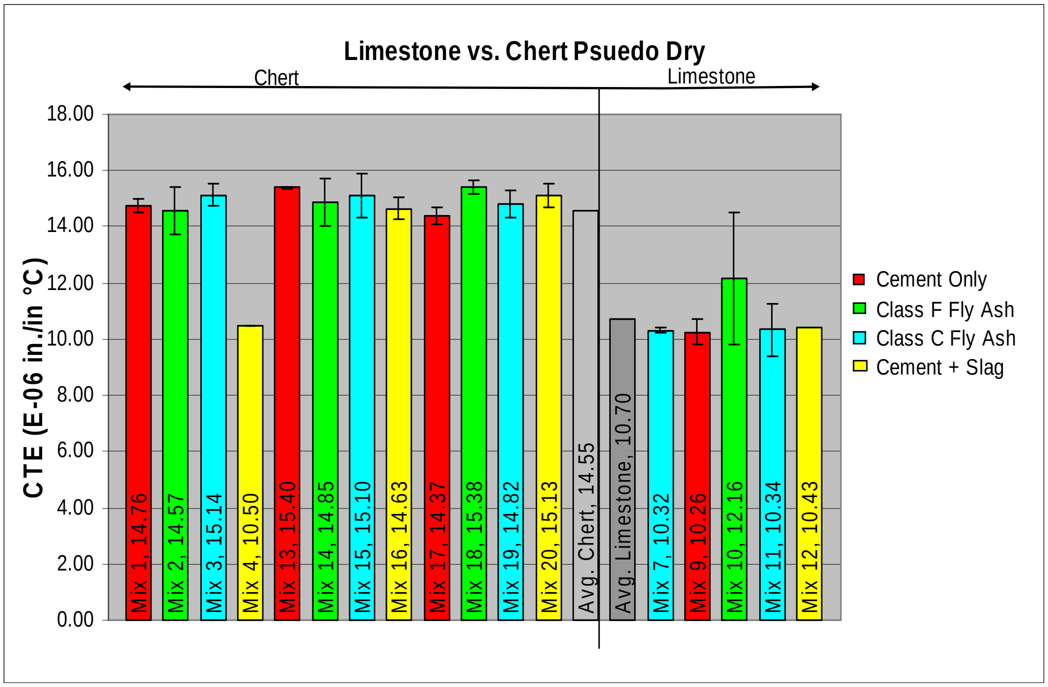


Fig. 4.9: Strain Gage Method CTE Values (Pseudo Dry Specimens)

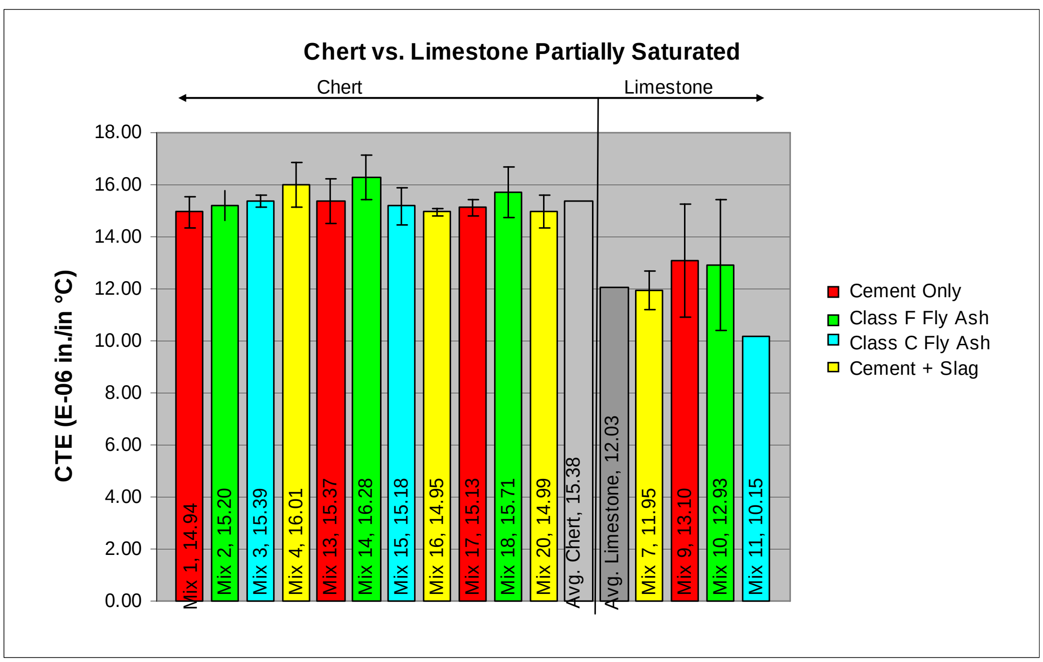


Fig. 4.10: Strain Gage Method CTE Values (Partially Saturated Specimens)

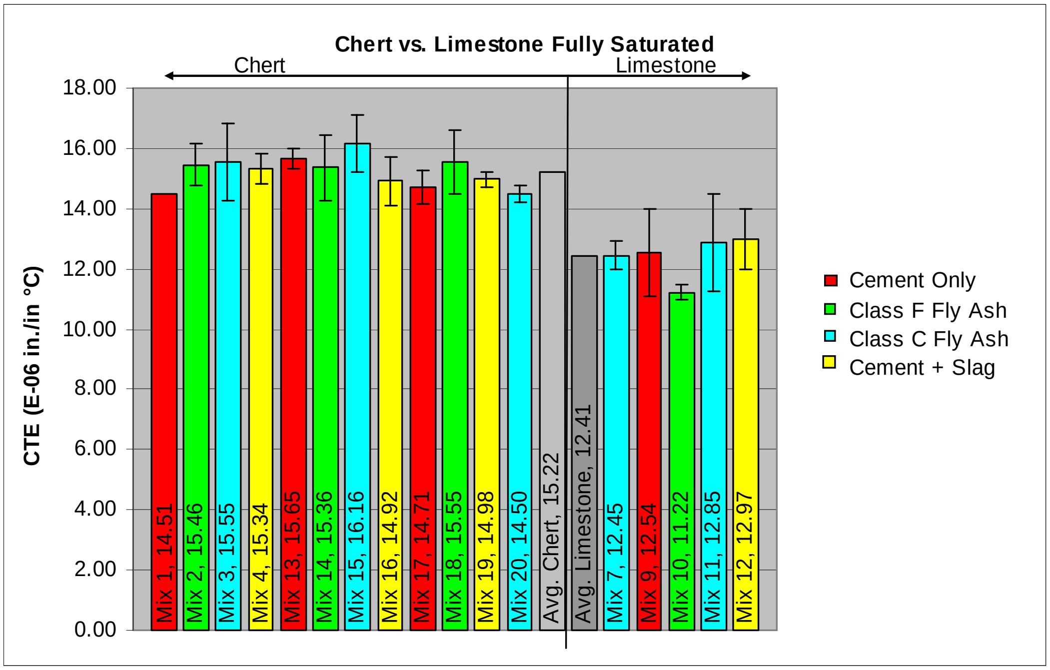


Fig. 4.11: Strain Gage Method CTE Values (Fully Saturated Specimens)

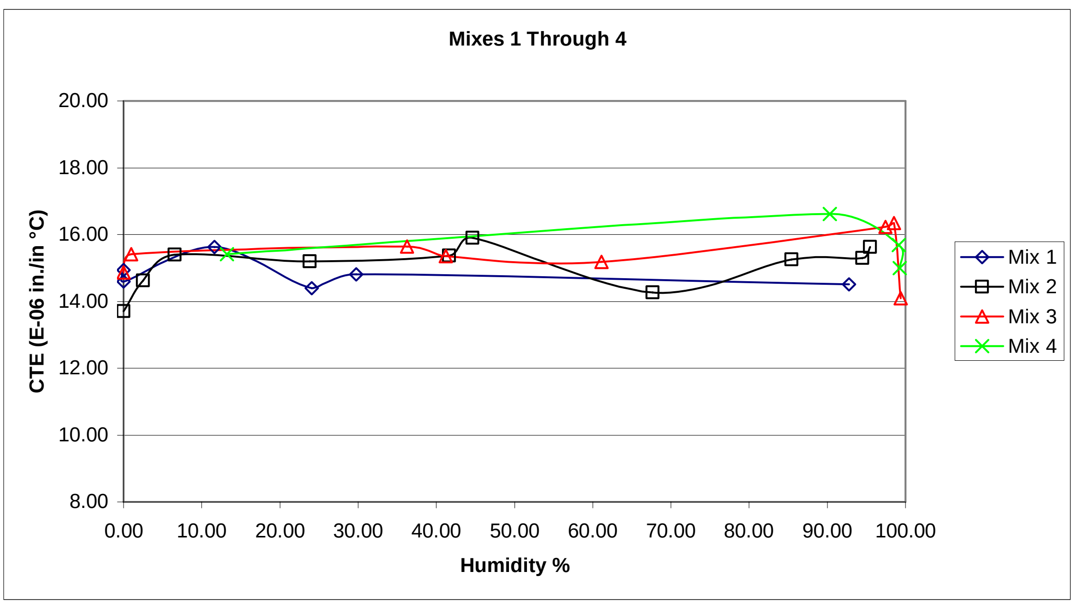


Fig. 4.12: Strain Gage Comparison of CTE Values for Mixes 1 Through 4

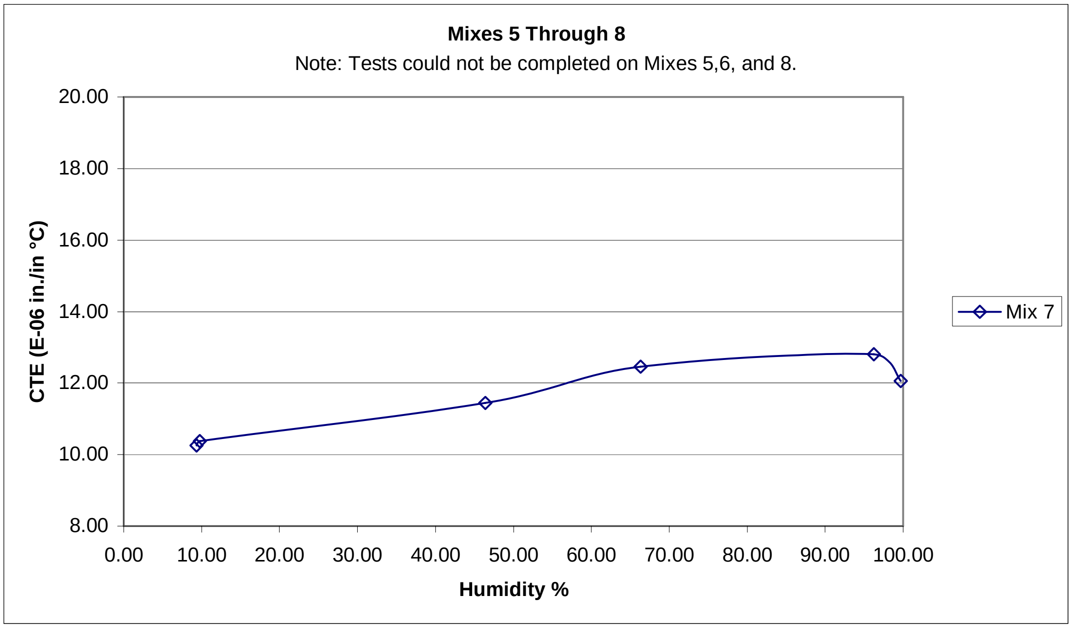


Fig. 4.13: Strain Gage Comparison of CTE Values for Mix 7

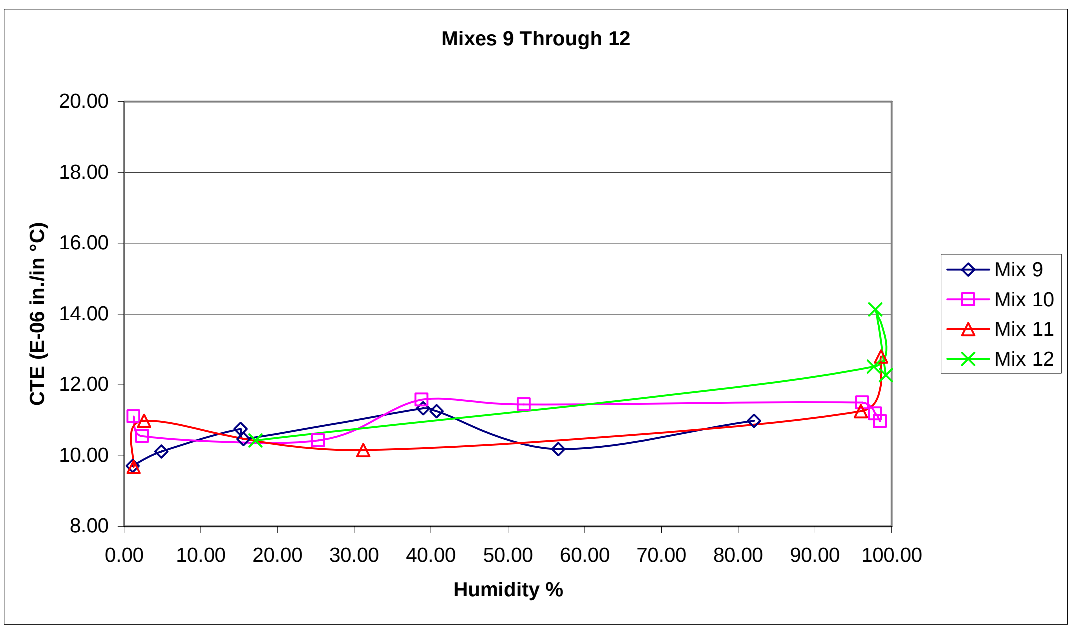


Fig. 4.14: Strain Gage Comparison of CTE Values for Mixes 9 Through 12

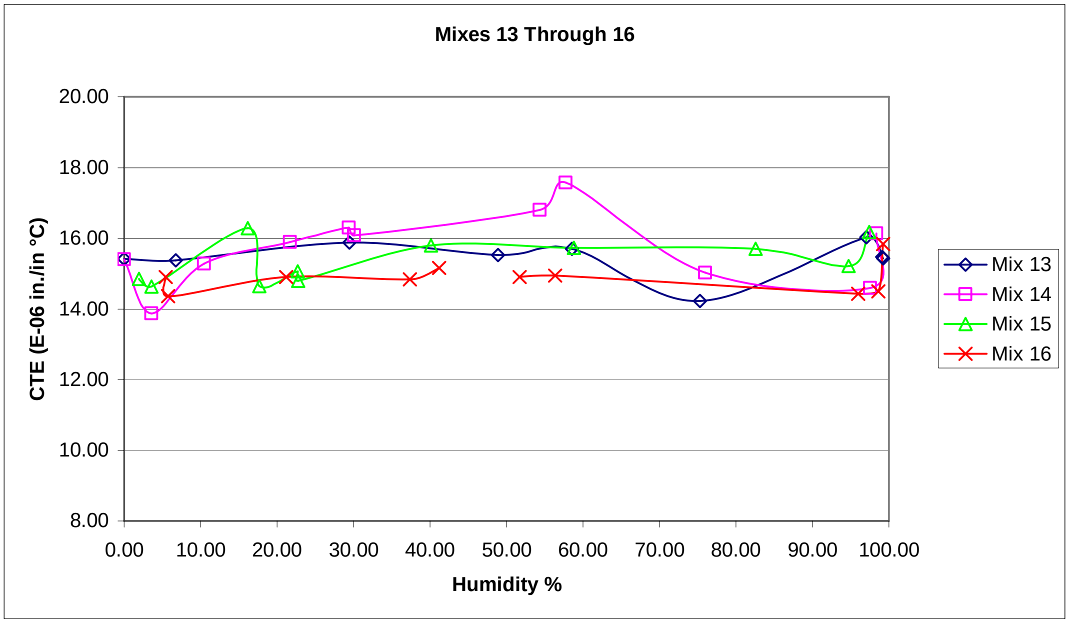


Fig. 4.15: Strain Gage Comparison of CTE Values for Mixes 13 Through 16

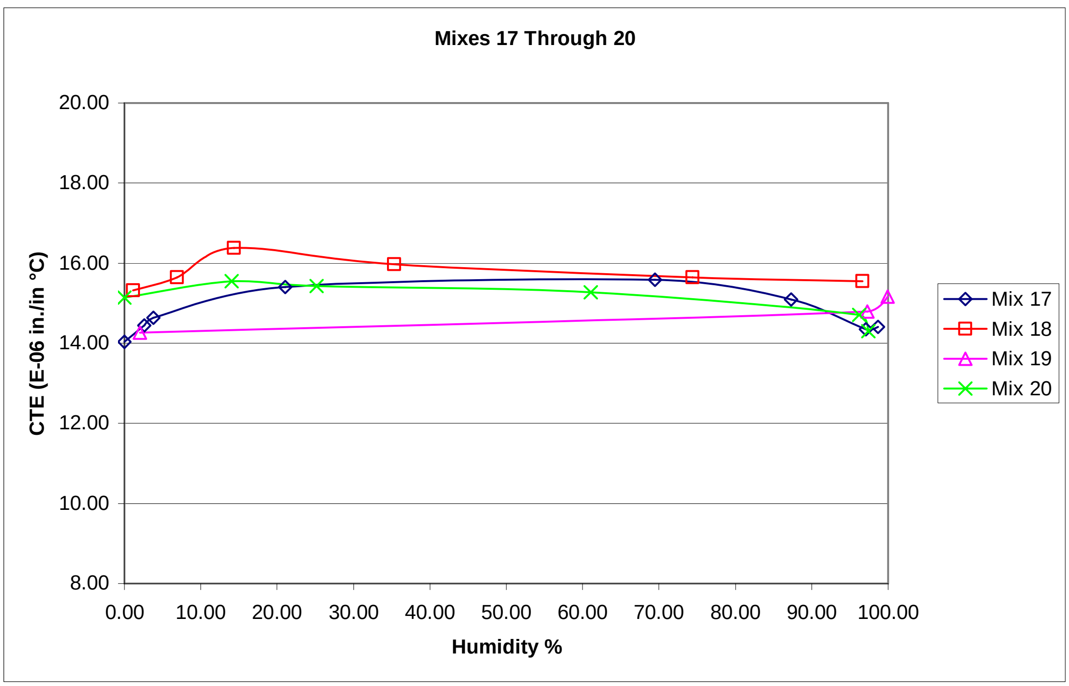


Fig. 4.16: Strain Gage Comparison of CTE Values for Mixes 17 Through 20

Viewing the results from the Strain Gage test in Figures 4.10 through 4.12 show again that the values of CTE for the specimens with chert aggregate are higher than those of the specimens with limestone aggregate except for all mixes of chert compared to limestone, unlike the results of the AASHTO method. However, the results for Figures 4.13 through 4.17 show that the humidity of each specimen had little effect on the CTE. Some things to consider, though, with the results from the strain gage test are:

1. The Strain Gage placement is in such a way that it measures localized strain as compared to overall strain of the AASHTO method. No calculations were used to determine a strain for localized stress.
2. Strain Gage method uses a third material, the adhesive, and no calculated strain due to the adhesive was considered in the calculation of CTE for the specimen.
3. The gage itself changes CTE, as mentioned in Section 3.4.4, and there could be some error in the calculated strain of the gage. In our calculations we corrected for change in strain gage using the book "The Bonded Electrical Resistance Strain Gage" p. 349-53.
4. Overall, the greatest challenge was the control of humidity and quantity in each specimen. Although readings were obtained from humidity gages embedded in the specimens, values may not have been accurate for each. A further study is being considered to more accurately measure humidity inside the specimens.

Some statistical analysis yielded a maximum increase of 32% in the case of Mix 11 and a maximum decrease of 0.01% for Mix 16 when compared between mixes with different saturations. The mean variation was 5.36% with a standard deviation of 7.29%.

4.3 Danish Test

The following Figure 18 through 25 results are those obtained from the Danish Test portion of this project:

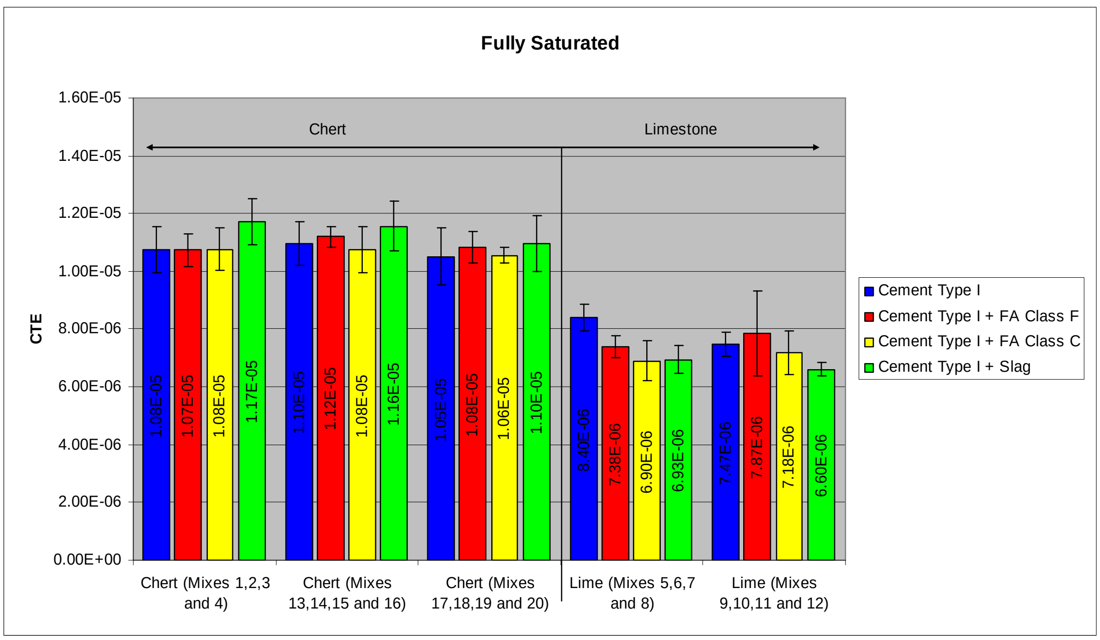


Fig. 4.17: Danish Test Comparison of Mixes at Fully Saturated State

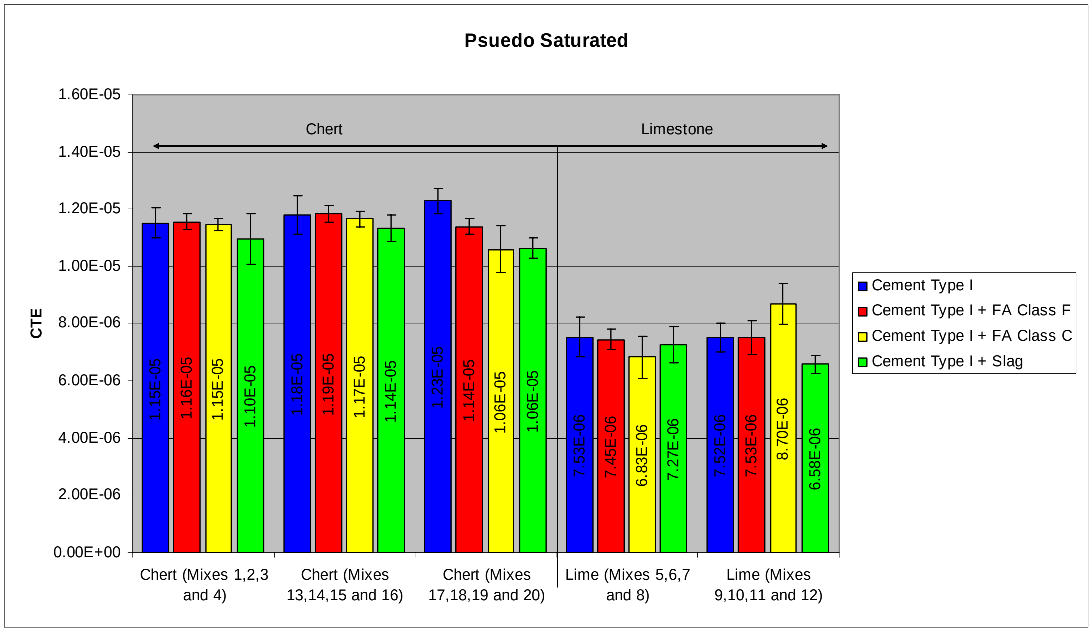


Fig. 4.18: Danish Test Comparison of Mixes at Pseudo Saturated State

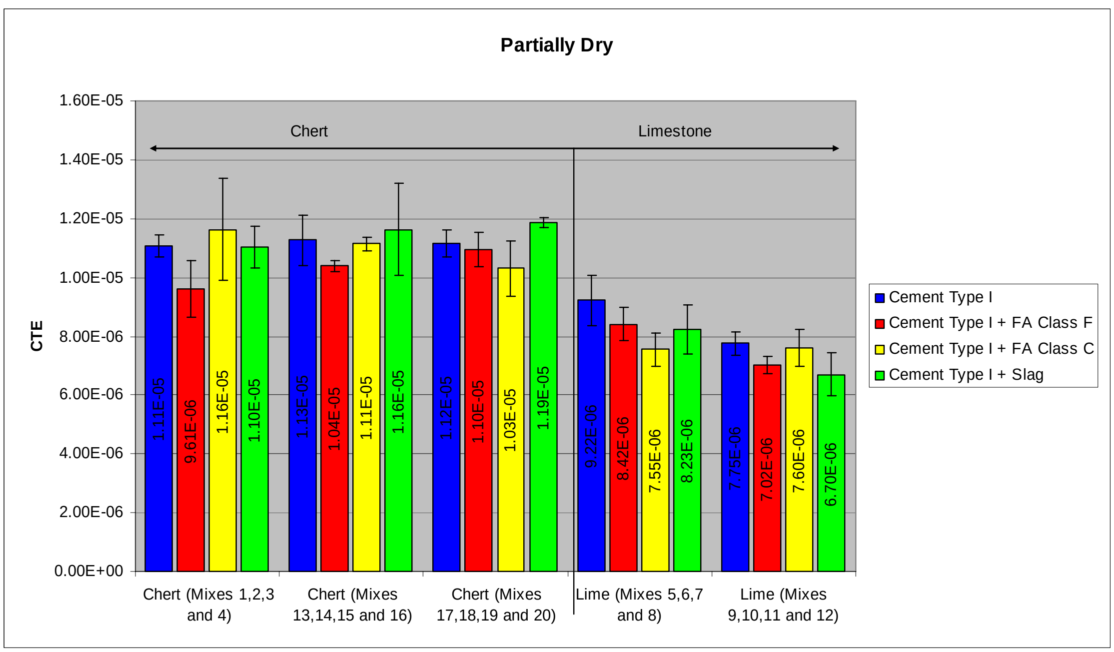


Fig. 4.19: Danish Test Comparison of Mixes at Partially Dry State

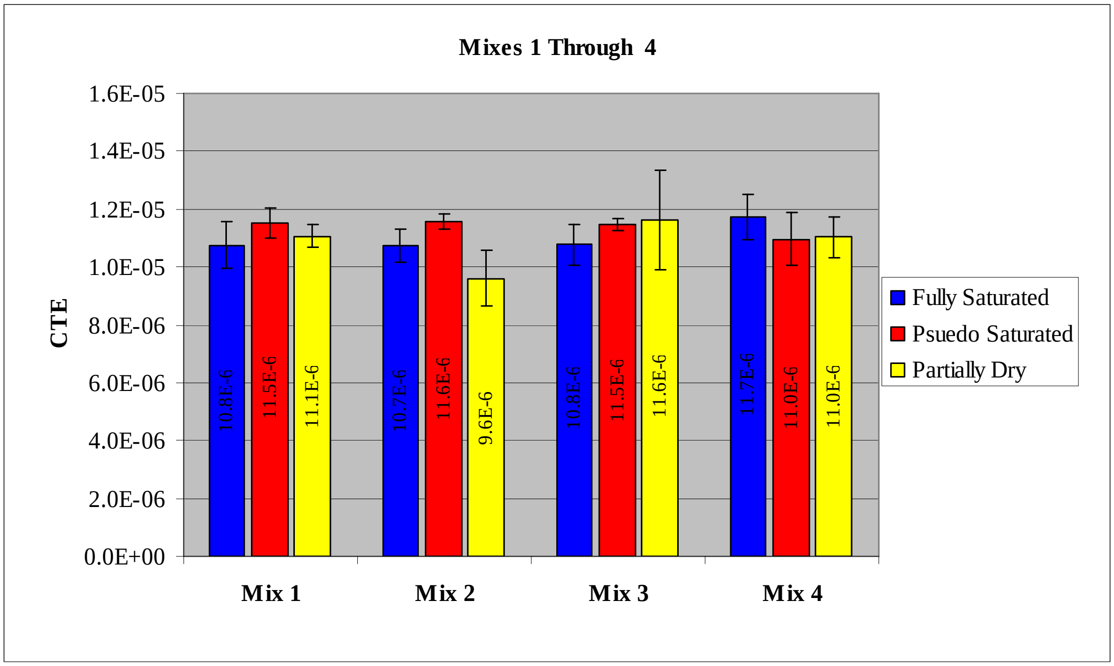


Fig. 4.20: Danish Test Mixes 1 Through 4 for Comparison

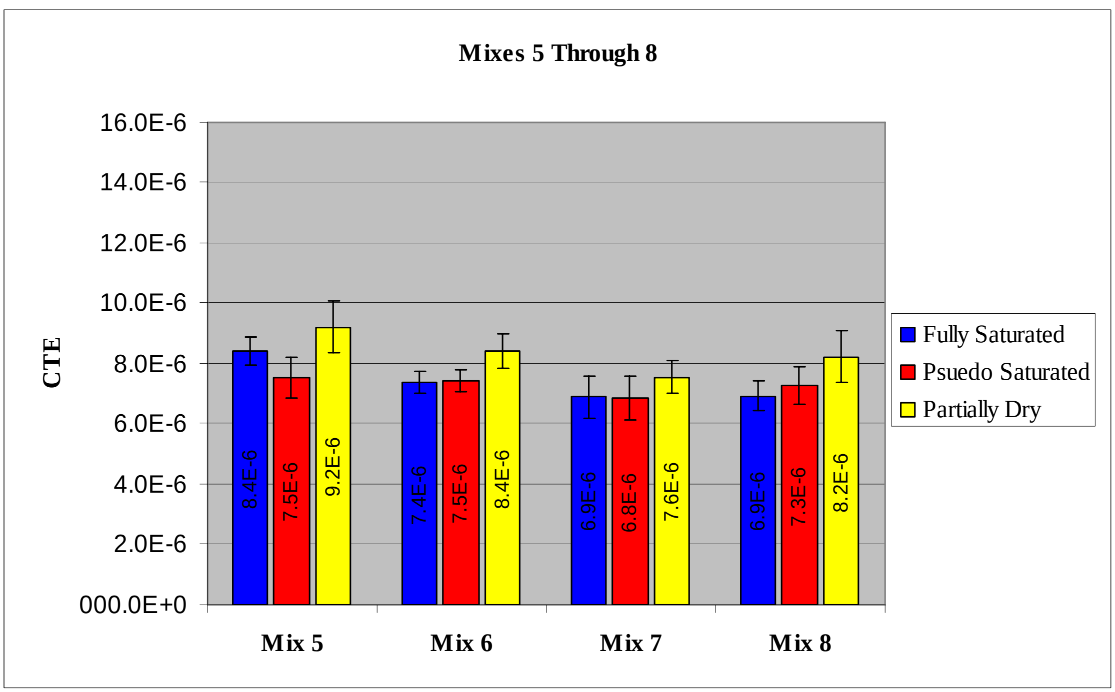


Fig. 4.21: Danish Test Mixes 5 Through 8 for Comparison

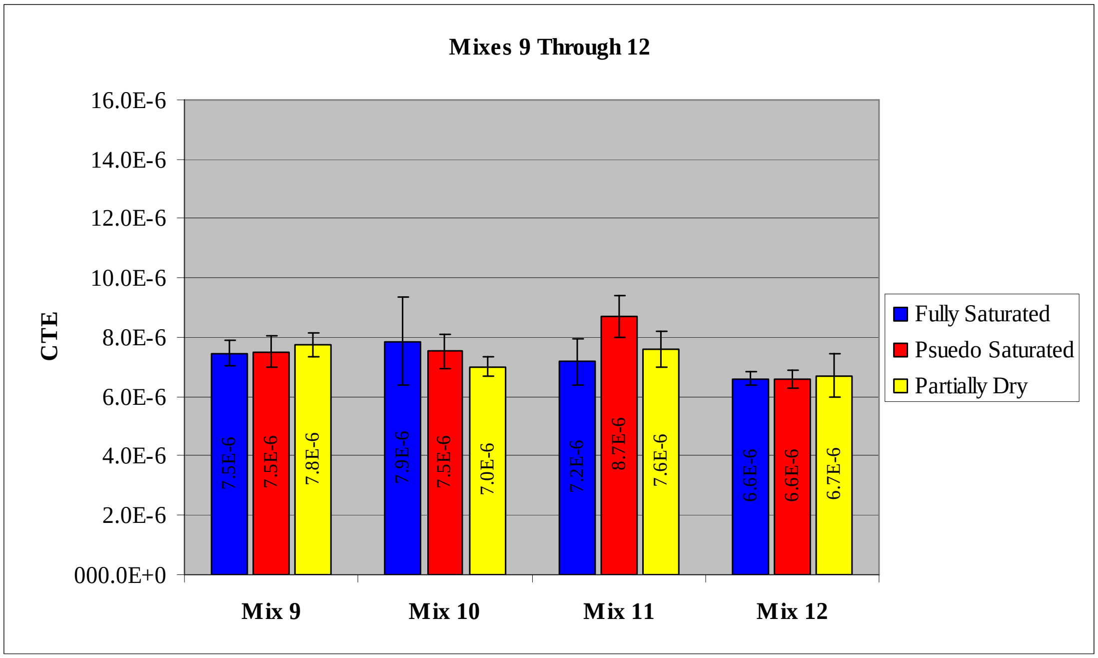


Fig. 4.22: Danish Test Mixes 9 Through 12 for Comparison

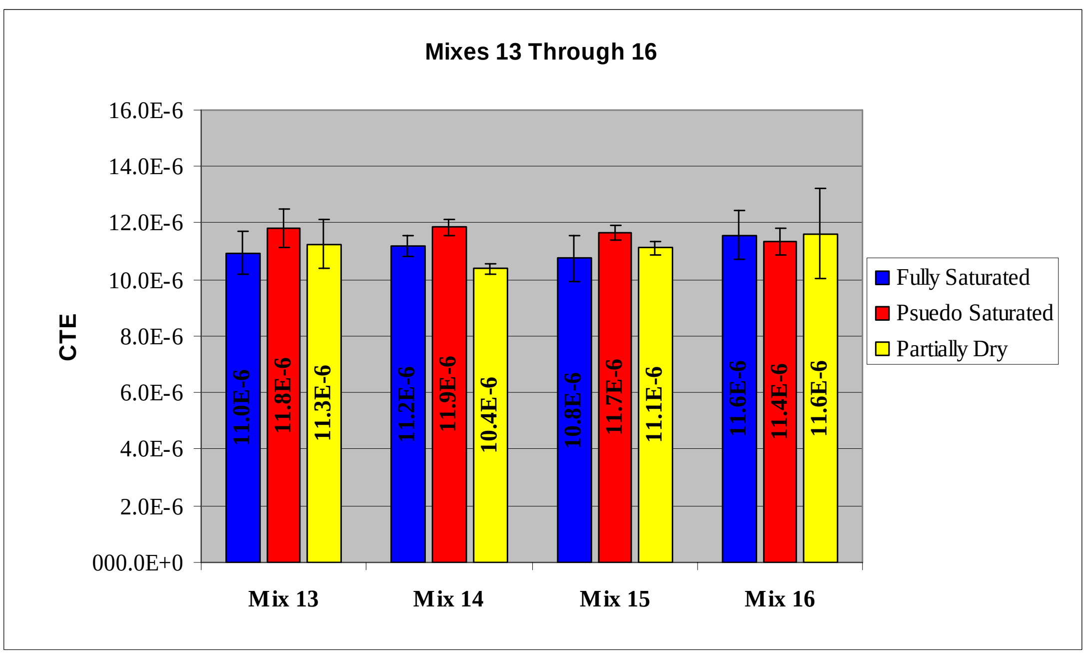


Fig. 4.23: Danish Test Mixes 13 Through 16 for Comparison

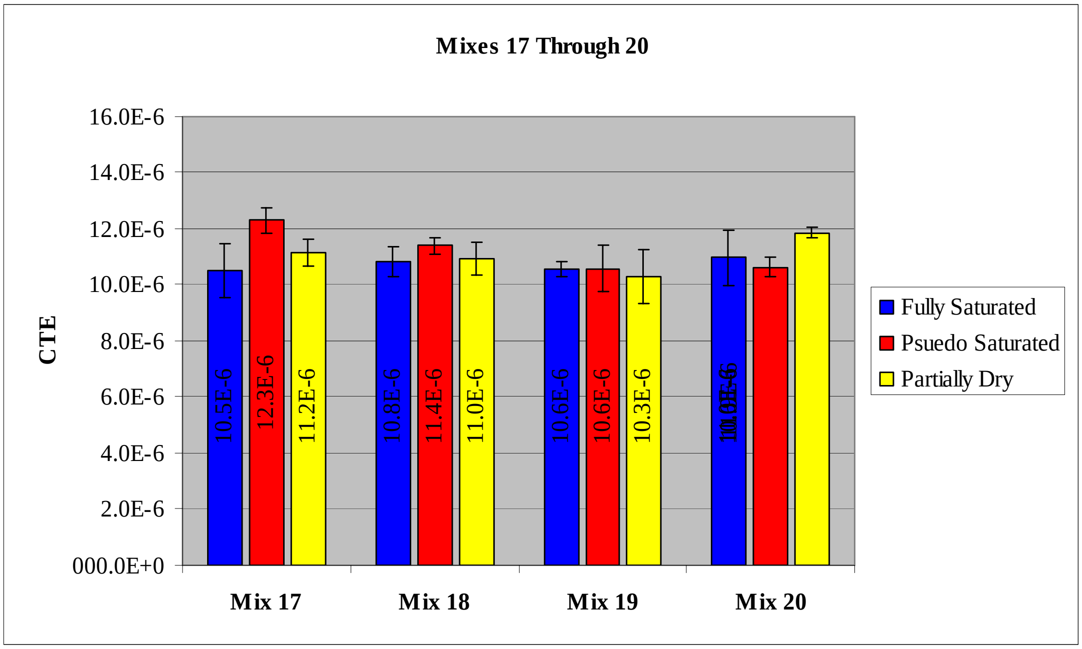


Fig. 4.24: Danish Test Mixes 17 Through 20 for Comparison

Figures 4.18 through 4.20 yielded the same result as previous tests. Again, it can be concluded that all specimens with chert aggregate have higher values of CTE than those of limestone, the same as the results compared in the Strain Gage test. There was, however, no common trend of maximum CTE being at 70% saturation though as compared to statements by Mehta (Mehta, 1986). One thing that could be considered in the results of the Danish method is that measuring disks were placed on the bottom and both sides of each specimen where on the bottom more aggregates may have gathered causing variations in readings if compared to those on the side. Some statistical analysis of the results yielded a maximum increase of 18.75% in the case of Mix 8 and a maximum decrease of 0.58% for Mix 16 when compared between mixes and their varied saturations. The mean variation was 2.97% with a standard deviation of 7.68%.

CHAPTER 5

CONCLUSIONS

1. Different methods led to different CTE values for all the cases studied (all types of aggregates and blends of cements).

2. Both, the Strain Gage method and Danish T1-B 101 methods measure localized strain instead of overall strain. On the other hand, the AASHTO TP-60 method considered the overall response of the test specimen which makes it more reliable. Moreover, in the case of the Danish method, metallic disks are placed on the surface of the test specimens using adhesive. Neither the coefficient of expansion of the adhesive nor the disks are corrected for. The Danish specimens do not have surfaces that are cut and measuring points then placed directly onto surfaces of the aggregate and in the same way as the AASHTO TP-60 test where the ends are cut and the LVDT device measures from them directly with the exception of epoxy coated specimens. The cementious material between the measuring points and the aggregate inside may cause some variation in values. Based on test limitations in this report, we conclude that the AASHTO TP-60 test is the most accurate test for calculation of CTE.

3. The predominate factor affecting the CTE of concrete is the aggregate type. This is because in the concrete compared in this study a ratio of 72% coarse aggregate per volume was used. Almost all specimens made using chert yielded higher CTE values than those of limestone for all types of blended cements for all saturation levels.

4. Using AASHTO TP-60 technique, our study found that partially saturated cases are more critical than those of dry or fully saturated cases. This is in stronger agreement with studies conducted by Neville (see Figure 2.1, page 6 in this report). Thus, evaluation CTE of partially saturated cases is needed to obtain accurate estimation of the amount of shrinkage due to thermal variation in pavement design. We recommend that the CTE obtained from the AASHTO TP-60 be modified by some factor of safety.

5. Using both the Danish Method TI-B 101 and the Strain Gage method, the level of saturation had a minor effect on the value of CTE.

6. Specimen shape may have an effect on the CTE due to the variation in CTE values when compared between the three methods. The values of CTE for the Danish Method TI-B 101 were higher than those of the AASHTO TP-60 method. This in agreement with the effect of specimen shape studied by Yang and, etc. (Yang, et al., 2003).

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