Quantifying Coefficient of Thermal Expansion Values of Typical Hydraulic Cement Concrete Paving Mixtures

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16. Abstract

A laboratory investigation was conducted to determine the coefficient of thermal expansion (CTE) of a typical MDOT concrete paving mixture made with coarse aggregate from eight different sources. The primary aggregate class included limestone, dolomite, slag, gravel and trap rock. The CTE was determined using the provisional AASHTO TP60 protocol. Three replicate test specimens were fabricated for each mixture-age combination. The test specimens were moist cured for 3, 7, 14, 28, 90, 180, and 365 days prior to testing. The average measured CTE values ranged from 4.51 to 5.92 $\mu\varepsilon$ /^{o}F (8.11 to 10.65 $\mu\varepsilon$ /^{o}C). The test results indicated that aggregate geology, specimen age at the time of testing and the number of heating-cooling cycles that the specimen is subjected to have a statistically significant (at a confidence level of 95%) impact on the magnitude of measured CTE. Furthermore, the report also discusses the practical (significance) impact of the test variables on the transverse cracking performance of jointed plain concrete pavements.

17. Key Words Coefficient of thermal expansion; Portland cement concrete; coarse aggregate; jointed concrete pavement; AASHTO TP60	**18. Distribution Statement** No restrictions. This document is available to the public through the Michigan Department of Transportation.

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EXECUTIVE SUMMARY

The coefficient of thermal expansion (CTE) is defined as the change in unit length per unit change in temperature. It is usually expressed in microstrain (10^{-6}) per degree Celsius (με /^{o}C) or microstrain (10^{-6}) per degree Fahrenheit (με/^{o}F). The CTE of Portland Cement Concrete (PCC) is an important parameter in analyzing thermally induced stresses in jointed concrete pavements (JCPs) during the first 72-hours after paving and over the design life. The magnitude of CTE is also important in determining the amount of joint movement, slab length and joint sealant reservoir design.

The new Mechanistic-Empirical Pavement Design Guide (M-E PDG) allows for the input of CTE at three levels (quality of data); (i) Level 1 of CTE determination involves direct measurement in accordance with a test protocol developed by American Association of State Highway and Transportation Officials (AASHTO) titled AASHTO TP60, "Standard Test Method for CTE of Hydraulic Cement Concrete;" (ii) Level II of CTE determination uses a weighted average of the constituent values based on the relative volumes of the constituents (as shown in the equation below) in which α is the CTE of the constituent and V is the volumetric proportion of the constituent in the PCC mix.; and (iii) Level III of CTE estimation is based on historical data.

Currently, the Michigan Department of Transportation (MDOT) does not call for the determination of CTE for the design of concrete pavements. However, CTE has a significant bearing on the computation of concrete pavement response and performance prediction in the new M-E PDG. For the successful implementation of the new design procedure the determination of CTE is necessary. In light of this the Michigan Department of Transportation funded a two year research project to document the Level I magnitudes of CTE for Portland Cement Concrete paving mixtures commonly used in the state.

A laboratory investigation was conducted to determine the CTE of a typical MDOT concrete paving mixture made with coarse aggregate from eight different sources. The primary aggregate class included limestone, dolomite, slag, gravel and trap rock. The CTE was determined using the provisional AASHTO TP60 protocol. Three replicate test specimens were fabricated for each mixture-age combination. The test specimens were moist cured for 3, 7, 14, 28, 90, 180, and 365 days prior to testing. The average measured CTE values ranged from 4.51 to 5.92 με /^{o}F (8.11 to 10.65 με /^{o}C). The test results indicated that aggregate geology, specimen age at the time of testing and the number of heating-cooling cycles that the specimen is subjected to have a statistically significant (at a confidence level of 95%) impact on the magnitude of measured CTE. Furthermore, the report also discusses the practical (significance) impact of the test variables on the transverse cracking performance of jointed plain concrete pavements.

Based on the laboratory investigation and the statistical analyses of the dataset it was concluded that:

- The magnitude of the measured CTE varied with aggregate geology. The measured CTE magnitudes for the various aggregate geologies compared favorably with the published values.
- Magnitude of the measured CTE is significantly (statistically) influenced by the age of the sample at the time of testing. It was found that the magnitude of the measured CTE at the early ages (3, 7, 14, 28 days) were significantly (statistically) different than the magnitudes determined at the end of 90, 180, and 365 days. However, operationally the impact of this difference on transverse cracking (as computed by the M-E PDG software for 14, 28, and 90 days) was not found to be significant.
- The number of heating-cooling cycles in CTE test affects the magnitude of CTE. The CTE value calculated based on the first cycle was higher than the values calculated based on second and third cycles. Statistically the CTE values based on second and third cycles were not different from each other.

- Coefficient of variance for the data set ranged from 2.5-6%. Approximately 98% of the data set has a δCTE between ± 0.3 με /oF (0.5 με /oC). It was observed that generally, concrete with higher CTE values is more sensitive to variability compared to concrete with low CTE value

M-E PDG software along with statistical analysis were used to investigate the impact of CTE value and its interaction with other design factors on long term performance of jointed concrete pavements in cracking.

It was found that the impact of CTE, slab thickness, and joint spacing on transverse cracking were statistically significant. Practical significance was evaluated by comparing the results of the analyses with published criteria on percent slabs cracked.

It was observed that, thinner slab, longer joint spacing, and higher CTE values resulted in increased percent of slabs cracked over the age of a pavement.

Based on the results from a number of analyses it was observed that when comparing the effect of CTE combined with the effect of slab thickness or joint spacing, the combined effect of CTE and joint spacing is more significant than the effect of CTE and slab thickness.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The coefficient of thermal expansion (CTE) is defined as the change in unit length per unit change in temperature. It is usually expressed in microstrain (10^{-6}) per degree Celsius ($\mu\varepsilon/^{o}C$) or microstrain (10^{-6}) per degree Fahrenheit ($\mu\varepsilon/^{o}F$). The CTE of Portland Cement Concrete (PCC) is an important parameter in analyzing thermally induced stresses in jointed concrete pavements (JCPs) during the first 72-hours after paving and over the design life. The magnitude of CTE is also important in determining the amount of joint movement, slab length and joint sealant reservoir design. The selection of CTE in the design process can impact pavement performance in the following ways:

Table 1-1. Influence of CTE on Pavement Performance (Based on Reference 1)

Pavement Distress	Role of CTE
Premature cracking due to excessive longitudinal slab movement	High CTE can potentially induce axial movement. This axial movement if restrained by slab-friction can lead to cracking
Mid-panel cracking	High curling stresses due to high temperature gradients and CTE.
Faulting and corner cracking	Higher corner deflections due to negative curling-which is a function of temperature gradients and CTE.
Joint spalling	Failure of joint sealant due to joint opening and closing.
Crack spacing and width in continuously reinforced concrete pavements (CRCP)	The magnitude of CTE determines the closeness and width of cracks and in turn impacts the load transfer efficiency of the crack.

The new Mechanistic-Empirical Pavement Design Guide (M-E PDG) allows for the input of CTE at three levels (quality of data); (i) *Level 1* of CTE determination involves direct measurement in accordance with a test protocol developed by American Association of State Highway and Transportation Officials (AASHTO) titled AASHTO TP60, "Standard Test Method for CTE of Hydraulic Cement Concrete;" (ii) *Level II* of CTE determination uses a weighted average of the constituent values based on the relative volumes of the constituents (as shown in the equation below) in which α is the CTE of the constituent and V is the volumetric proportion of the constituent in the PCC mix.; and (iii) *Level III* of CTE estimation is based on historical data.

$$\alpha_{PCC} = \alpha_{AGGREGATE} * V_{AGGREGATE} + \alpha_{PASTE} * V_{PASTE}$$

The greatest potential for error is associated with Level III data quality, because PCC materials vary considerably. Realistic data for the types of materials being used in concrete mixtures are rarely available and, if they are available, they are likely to be based on a specific PCC mixture. The M-E PDG design protocol provides a platform for studying the interaction between CTE and pavement performance based on typical Michigan Department of Transportation (MDOT) structural, material and climatic inputs.

1.2 Problem Statement

The recently completed M-E PDG uses CTE as one of the parameters to characterize the thermal properties of PCC paving mixture. The CTE of the PCC mixture is a key parameter input for computing response parameters such as: (i) joint movement, (ii) crack spacing and width for CRCP and (iii) curling stresses. These response parameters in turn influence performance prediction.

Currently MDOT does not call for the determination of CTE for the design of concrete pavements. However, CTE has a significant bearing on the computation of concrete pavement response and performance prediction in the new M-E PDG. For the successful implementation of the new design procedure the determination of CTE is necessary.

1.3 Research Objectives and Significance

The proposed project was partitioned into two phases. *Phase I* of the study focused on:

- Researching the standard test procedures for conducting the CTE test.
- Documenting work done in this area by other state DOTs and universities.
- Developing a test matrix representing the various mixtures for the State of Michigan.

Phase II of the study focused on

- Executing the approved test matrix developed in Phase I.
- Reporting the results obtained from the testing phase.
- Recommending input ranges for the execution of the new design guide.

1.4 Research Plan

The project was divided into two work phases. *Phase I* of the study focused on; (i) researching the standard test procedures for conducting the CTE test; (ii) documenting work done in this area by other state DOTs and universities; and (iii) developing a test matrix representing the various mixtures for the State of Michigan. *Phase II* of the study focused on; (i) executing the approved test matrix developed in Phase I; (ii) reporting the results obtained from the testing phase; and (iii) recommending input ranges for the execution of the new design guide. The project objectives were accomplished through the execution of six tasks.

1.5 Report Organization

Chapter 2 includes the literature review and synthesis of the state-of-the-practice. In Chapter 3 the experimental program is presented in detail which includes information about various test protocols carried out during the two year research period. The results are discussed in Chapter 4 which includes the results of statistical analyses and in Chapter 5 conclusions are presented. References and appendices are presented subsequently.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A limited number of laboratory studies have been conducted to evaluate different test methods for CTE determination, to identify variables that have an influence on the magnitude of CTE, and to investigate the effects of PCC CTE on concrete pavement performance.

This literature review presented in this chapter is divided into two sections. The first section summarizes information from literature investigating the impact of test variables on the magnitude of CTE and the impact of CTE on pavement performance of jointed concrete pavements. The second section summarizes the various test methods used to measure the magnitude of CTE for concrete.

The information presented in this chapter was obtained from (i) published journal articles, (ii) proceedings of various domestic and international conferences, and (iii) published research reports.

2.2 Literature on Variables Affecting CTE Value and CTE Impact on Pavement Performance

In a laboratory study conducted by Alungbe, Tia and Bloomquist *(2)* in 1992, the effects of aggregate type, water to cement ratio, curing, and specimen condition on the magnitude of CTE were investigated. Three types of aggregate were investigated as part of this study. Porous limestone, dense limestone, and river gravel. Three combinations of water to cement ratio and cement content were studied as well as two curing durations (28 and 90 days). Another variable was the specimen condition with two levels, water-saturated, and oven-dried.

A length comparator was used to measure the length changes of specimens. Specimens were square prisms with dimensions 3 in.×3 in.×11.25 in.

The authors reported that concrete samples fabricated using porous limestone had a CTE that ranged from 5.42 to 5.80 $\mu\varepsilon/^{o}F$ (9.76 $\mu\varepsilon/^{o}C$ to 10.44 $\mu\varepsilon/^{o}C$), concrete samples produced from dense limestone had a range of 5.82 to 6.14 $\mu\varepsilon/^{o}F$ (10.48 $\mu\varepsilon/^{o}C$ to 11.05 $\mu\varepsilon/^{o}C$), and concrete samples made of gravel coarse aggregate had a CTE range of 6.49 to 7.63 $\mu\varepsilon/^{o}F$ (11.68 $\mu\varepsilon/^{o}C$ to 13.73 $\mu\varepsilon/^{o}C$). A statistical analysis (factorial design) was used to study the effect of different variables on CTE magnitude. Based on statistical analysis results, the authors concluded that aggregate type affects the CTE value, but water to cement ratio and cement content have "no effect" on the CTE. The water-saturated specimen had lower CTE values compared to oven-dried samples. There was no significant difference between samples with different curing durations in water-saturated specimens. However, the CTE values of the 28-day cured specimens were higher than the value of 90-day cured samples in oven-dried specimens. *(2)*

Moon Won at the University of Texas at Austin evaluated the effect of coarse aggregate content and 32 different aggregate types on the CTE and the effect of sample age, rate of heating-cooling cycle, and size of specimen on measured CTE values *(3)*. As part of this study, he suggested improvements to the AASHTO TP60 method.

The paper stated that the accuracy and repeatability of this test procedure greatly depends on the stability and accuracy of the displacement readings at 50 and 122 ^{o}F (10 and 50 ^{o}C). As an alternative, it was suggested that the correlation between temperature and displacement changes be used for determination of CTE which results in a repeatable and more accurate CTE test procedure. The testing apparatus and specimen conditioning is the same as in TP60, but the temperature and linear variable differential transformer (LVDT) displacement readings are recorded every minute. The CTE calculation method is also different from the TP60 method and is based on a regression analysis between temperature and displacement readings. It was stated that with the revised procedure, the difference between heating and cooling CTE values is smaller than the difference based on TP60 method resulting in a more accurate and repeatable method in comparison with AASHTO TP60 method.

The effect of concrete age was also investigated. Concrete cylinders were tested over a period of 3 weeks and it was found that the age of concrete had little effect on CTE for up to three weeks. This is illustrated in Figure 2-1.

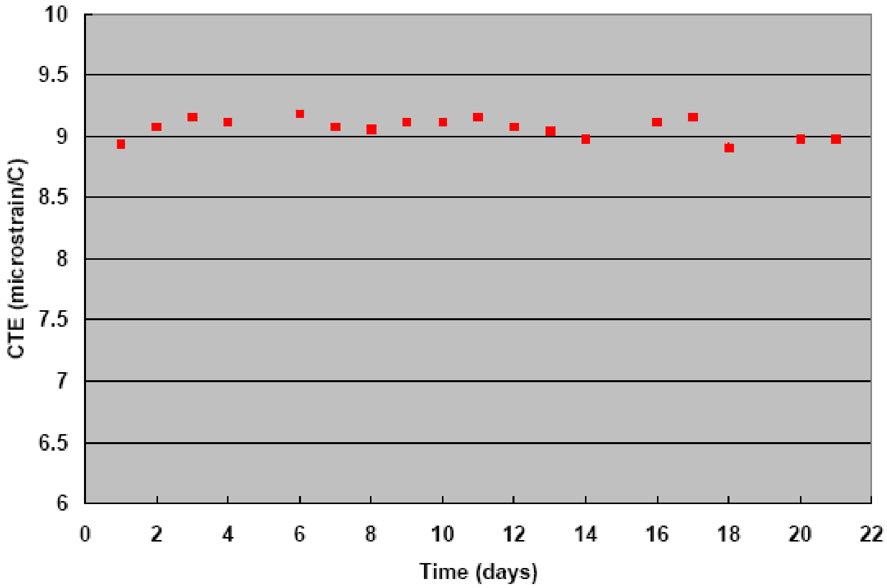


Figure 2-1. Variation of CTE over Time *(3)*

The effect of the rate of heating and cooling was studied. Two different rates were applied on a specific test specimen. The CTE value of the slow rate (0.93 ^{o}F/hr or 1.67 ^{o}C/hr) was found to be 5.82 $\mu\varepsilon/^{o}$F (10.48 $\mu\varepsilon/^{o}$C), and for the fast rate (14.83 ^{o}F/hr or 26.7 ^{o}C/hr) it was found to be 5.87 $\mu\varepsilon/^{o}$F (10.57 $\mu\varepsilon/^{o}$C). It was concluded that the rate of heating and cooling has little effect on the CTE value.

For the effect of the coarse aggregate content on the CTE value, the experimental results indicated an almost linear relationship between the %volume of coarse aggregate in the PCC mixture and the resulting CTE. The author concluded that there is a 0.03 $\mu\varepsilon/^{o}$F (0.045 $\mu\varepsilon/^{o}$C) change in the measured CTE per percent change in the coarse aggregate volume as shown in Figure 2-2.

For the effect of aggregate type on the CTE value, the CTE of concrete specimens made from coarse aggregate obtained from 32 producers in the state of Texas were measured. The results indicated that concrete specimens fabricated using the limestone aggregate sources had CTE values about 4.44 $\mu\varepsilon/^{o}$F (8.0 $\mu\varepsilon/^{o}$C) with a variability of 0.4 $\mu\varepsilon/^{o}$F (0.72 $\mu\varepsilon/^{o}$C)- whereas, concrete specimens fabricated with gravel as coarse aggregate had a CTE range of 4.50 $\mu\varepsilon/^{o}$F to 7.20 $\mu\varepsilon/^{o}$F (8.10 $\mu\varepsilon/^{o}$C to 12.96 $\mu\varepsilon/^{o}$C). The author concluded that this variability is attributed to the different geological make up of the gravel sources. The author states that this difference in variability between limestone and gravel might explain better performance and less variability in the performance of PCC pavements made with limestone coarse aggregate versus more variability in performance of the pavements made with gravel coarse aggregates as illustrated in Figure 2-3. *(3)*

Mallela, et al. *(1)* qualitatively investigated the practical significance of CTE variability on the performance of concrete pavements. The authors used the M-E PDG software for this investigation. The CTE results were based on hundreds of cores obtained from LTPP study sections throughout the United States.

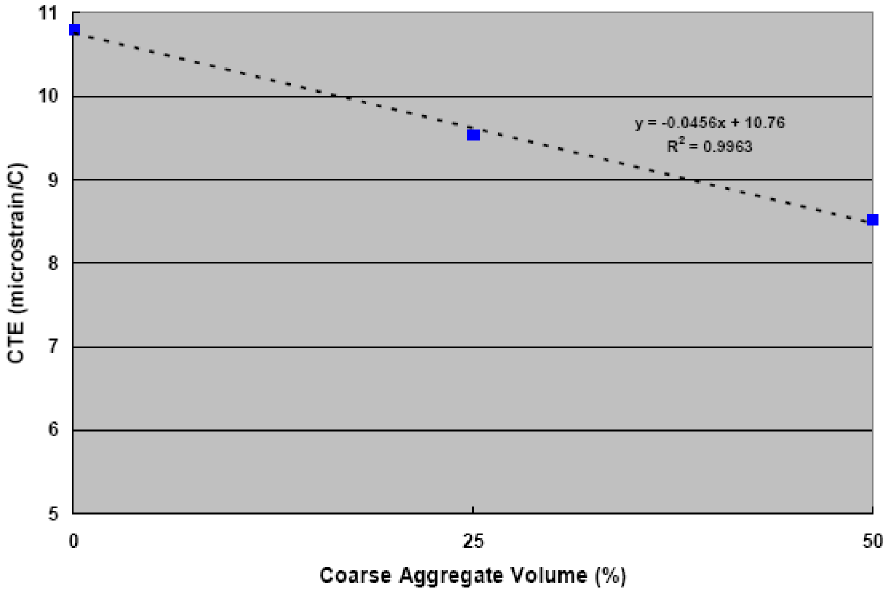


Figure 2-2. Effect of Coarse Aggregate Volume in Concrete on CTE ***(3)***

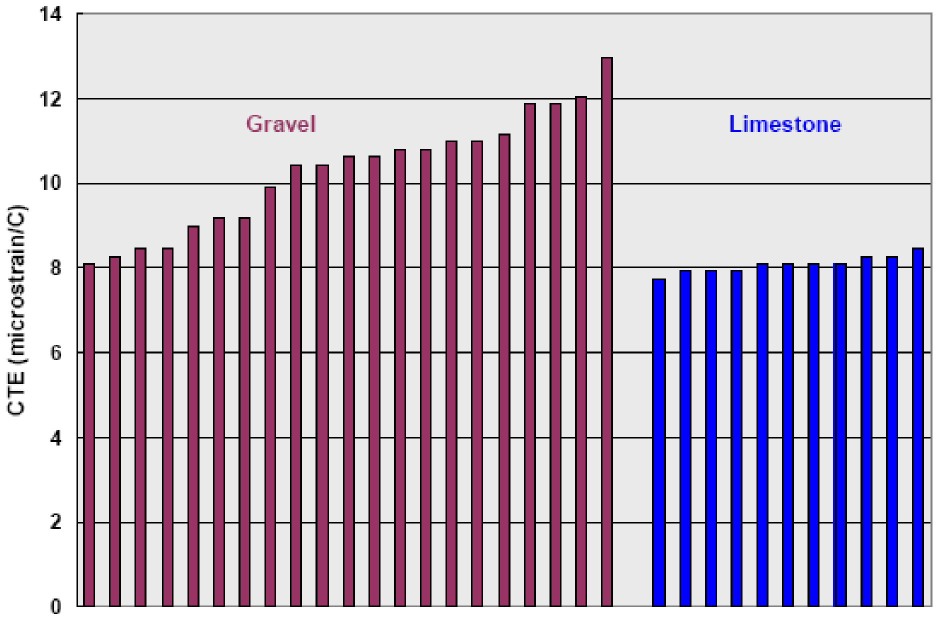


Figure 2-3. Effect of Coarse Aggregate Volume in Concrete on CTE ***(3)***

AASHTO TP60 test protocol was used to measure and calculate CTE values of the specimens. A total of 673 cores representing hundreds of pavement sections throughout the United States were tested and analyzed. The predominant aggregate type in each specimen was identified using different methods including optical microscopy. The general range of CTE values for the tested specimens in this study was between 5 and 7 $\mu\varepsilon/^{o}$F (9 and 12.6 $\mu\varepsilon/^{o}$C). It was observed that concrete made with igneous aggregate generally had lower average CTE than concrete made of sedimentary aggregate. It was also observed that with some exceptions, the variability (standard deviation) of the measured CTE was higher for concrete made with sedimentary aggregate than the concrete made with igneous aggregate.

It was stated that the PCC CTE affects joint spacing, joint load transfer, curling stresses, and corner deflections in JPCP, which in turn affect the transverse cracking, joint faulting, and smoothness. It was also stated that the interaction of CTE with other design features and site conditions plays a significant role in the extent of effect that CTE has on pavement performance. For example, higher CTE values coupled with a high temperature climate, is more detrimental than a climate with low temperatures. Similarly, the effect of CTE is more pronounced in pavements with larger joint spacing than the ones with shorter joint spacing. So, two types of sensitivity analyses were carried out on JPCP performance. In one analysis, only the effect of CTE on performance was investigated and in the other analysis, the interaction effects of CTE with other PCC design factors were studied.

In the first sensitivity analysis, a representative design with only the CTE being the variable was assumed. Three levels of CTE investigated were mean, mean plus two standard deviations, and mean minus two standard deviations for each aggregate type. The effect of PCC CTE on percent slabs cracked, faulting, and IRI is shown in Figures 2-4, 2-5, and 2-6 respectively. It was observed that CTE affects cracking, faulting, and IRI, but the CTE effect is more pronounced on predicted cracking than on mean joint faulting. It was also stated that in general, the higher the CTE, the poorer the pavement performance, and that the aggregate type has the largest influence on CTE value. Finally, the higher the variability in the measured CTE (for each aggregate type; aggregate source information is not known from the paper), the more unpredictable the pavement performance.

The critical design inputs and site conditions used to investigate the interaction effect of CTE and design factors were PCC flexural strength (500 and 750 psi) and elastic modulus (co-varied with flexural strength), transverse joint spacing (15 and 20 ft), and climatic conditions (wet freeze and dry-no freeze). Three levels of CTE (4.5, 5.5, and 7.0 με/°F or 8.10, 9.90, and 12.60 με/°C) were also considered in the analysis. It was found that in general, higher CTE values resulted in higher joint faulting, slab cracking, and roughness. Larger joint spacing and concrete strength increased the effect of CTE on joint faulting due to higher curling deflections (higher modulus of rupture relates to higher elastic modulus in the strength relationships used in M-E PDG). In wet freeze climate, higher joint faulting values were observed. Larger joint spacing and lower concrete strength resulted in amplified effect of CTE on transverse cracking. The CTE effect on IRI was more sensitive to concrete flexural strength. *(1)*

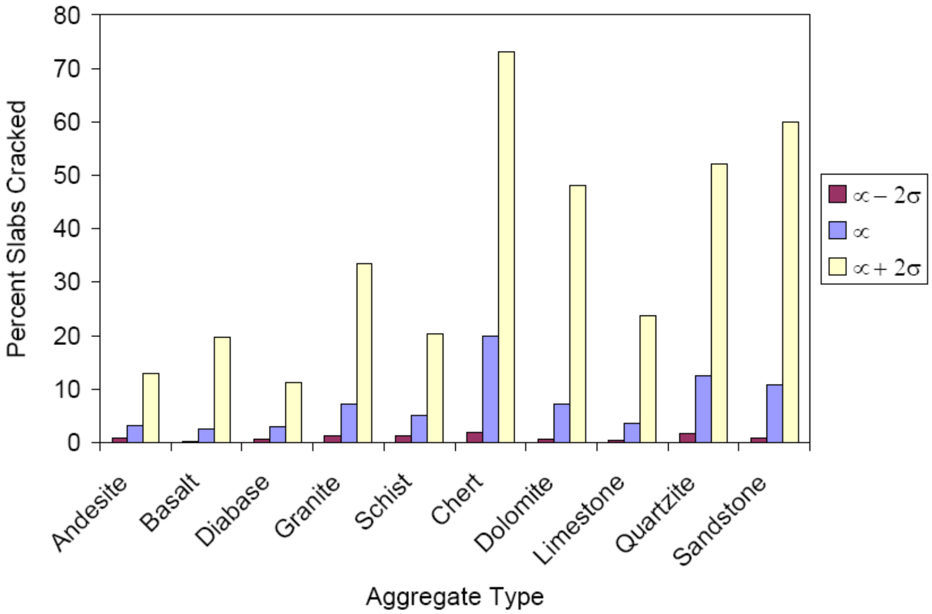


Figure 2-4. Effect of PCC CTE and its Variability on the M-E PDG Predicted Percent Slabs Cracked *(1)*

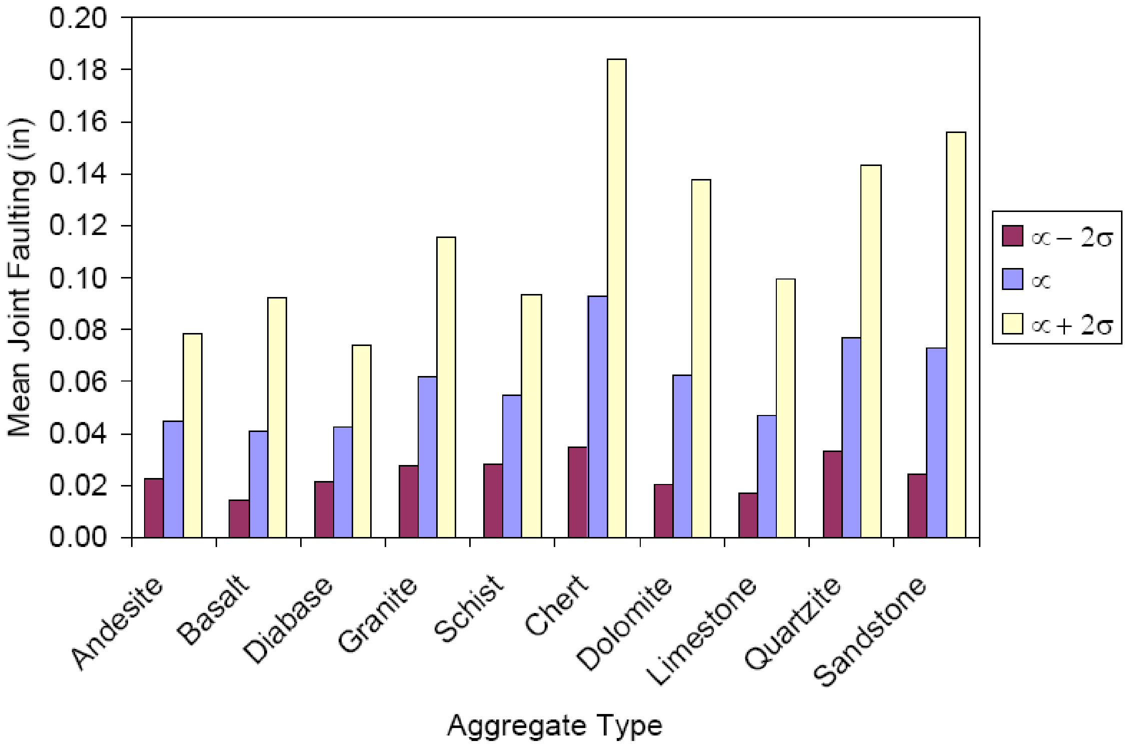


Figure 2-5. Effect of CTE and its Variability on the M-E PDG Predicted Mean Joint Faulting *(1)*

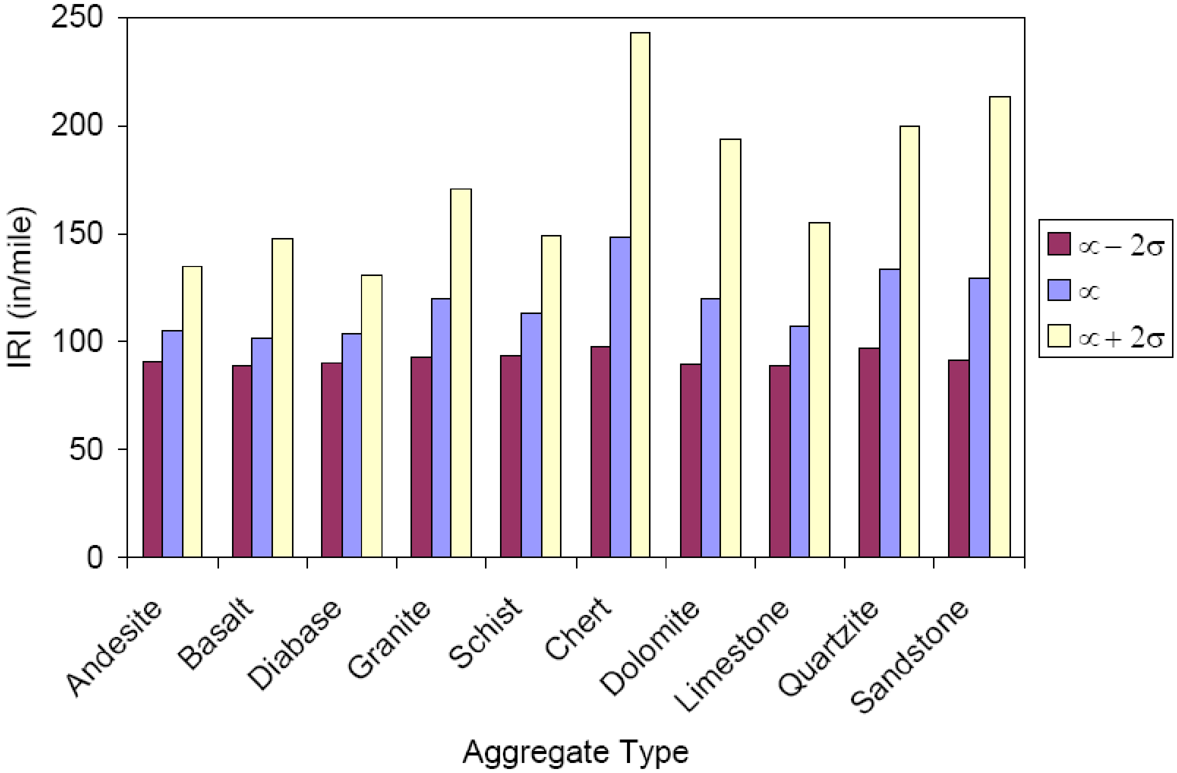


Figure 2-6. Effect of CTE and its variability on the M-E PDG predicted IRI *(1)*

An investigation was conducted by Naik, Chun, and Kraus at the University of Wisconsin Milwaukee *(4)* to quantify values for CTE of concrete in order to support the implementation of the M-E PDG program in Wisconsin.

Coarse aggregate from 15 sources were used in the fabrication of concrete specimens. Glacial gravel from six sources and dolomite from 5 sources were used. Quartzite, granite, diabase, and basalt each from one source were also used. CTE values were obtained according to the AASHTO TP60 test protocol. Three replicate specimens at the age of 28 days were tested. The cementitious materials proportion of the mixture design included 70% type I cement and 30% class C fly ash. In another part of the study, the effect of cementitious materials on CTE of concrete was evaluated. Four mixture designs were considered. Each mixture design included a different source of dolomitic aggregate. Cementitious materials used were cement, cement plus fly ash (two different mixtures), and cement plus ground granulated blast furnace slag (GGBFS).

As shown in Figure 2-7, the concrete made with quartzite showed the highest CTE value of 6.8 $\mu\varepsilon/^{o}F$ (12.2 $\mu\varepsilon/^{o}C$). The lowest CTE values were those of concrete made with diabase, basalt, and granite ranging from 5.2 to 5.3 $\mu\varepsilon/^{o}F$ (9.3 to 9.5 $\mu\varepsilon/^{o}C$). Concrete made with glacial gravels from six different sources had CTE values between 5.4 and 5.9 $\mu\varepsilon/^{o}F$ (9.7 and 10.7 $\mu\varepsilon/^{o}C$) and the CTE range for concrete made with dolomite from five different sources (Figure 2-8) was relatively uniform, between 5.8 to 6.0 $\mu\varepsilon/^{o}F$ (10.4 to 10.8 $\mu\varepsilon/^{o}C$).

According to this study, the types and sources of cementitious materials had a negligible influence on the concrete made with dolomite. The CTE was influenced very little (0.0 to 0.1 $\mu\varepsilon/^{o}F$ or 0.0 to 0.2 $\mu\varepsilon/^{o}C$) by the source of cement and class C fly ash, the use of fly ash versus GGBFS, and the use of cement versus cement plus class C fly ash. *(4)*

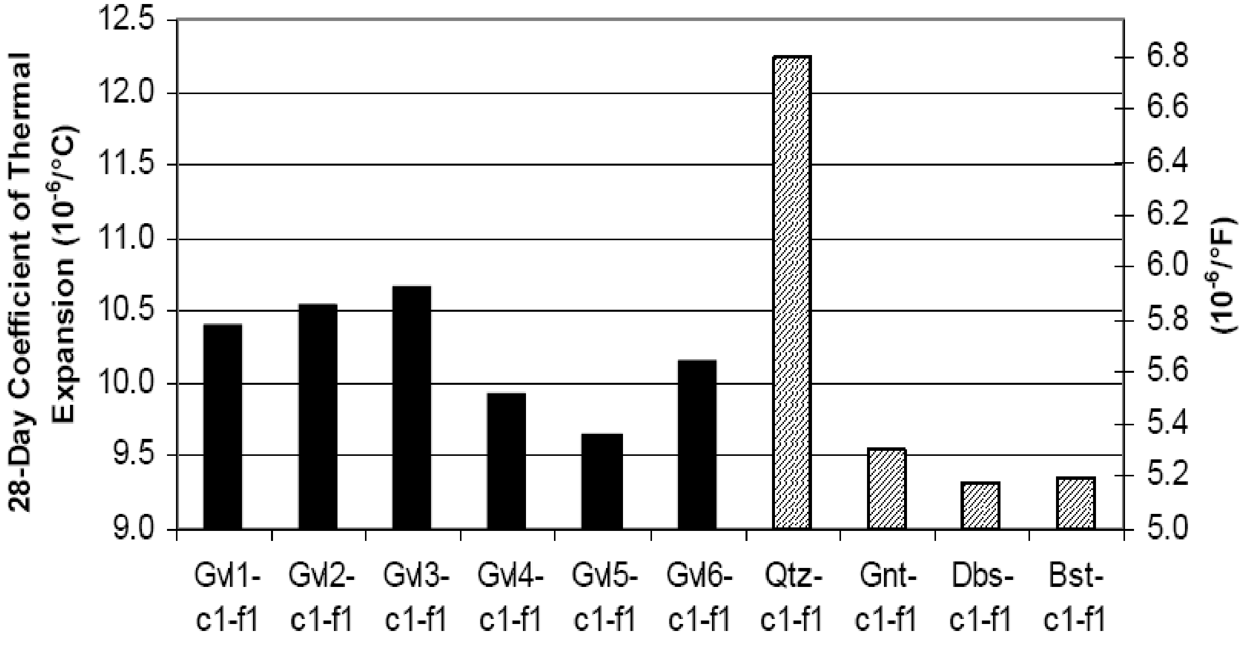


Figure 2-7. CTE of Concrete Made with Gravel, Quartzite, Granite, Diabase, or Basalt *(4)*

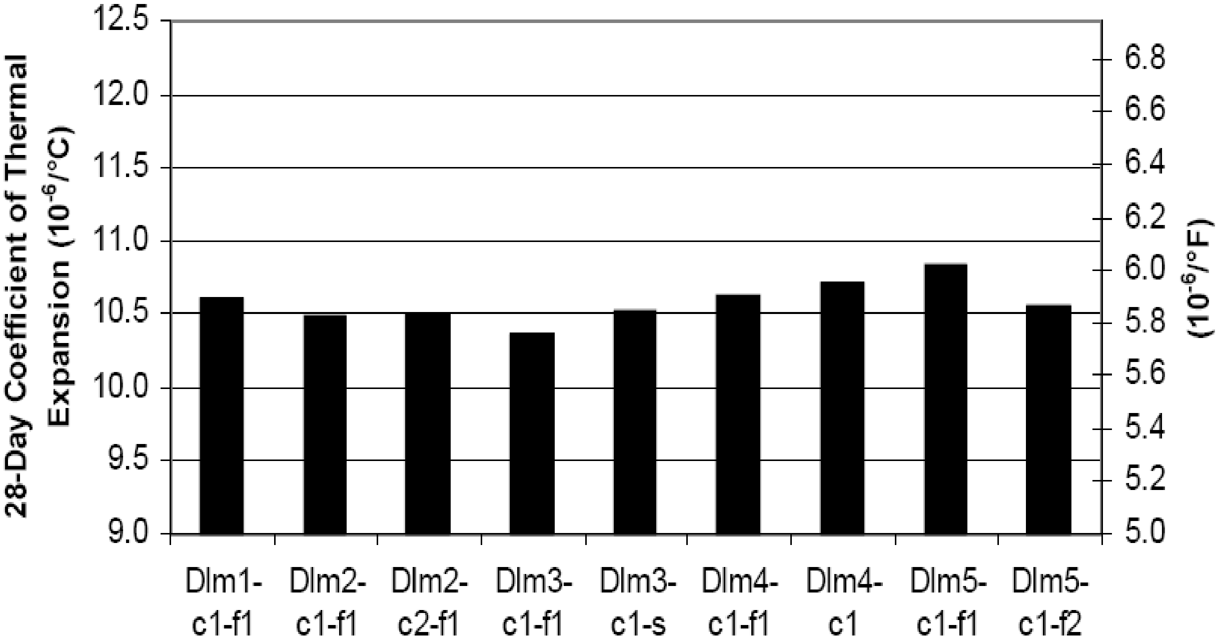


Figure 2-8. CTE of Concrete Made with Dolomite and Different Cementitious Materials *(4)*

Hossain, et al. *(5)* investigated the effect of the hierarchical input levels of CTE on the performance of jointed concrete pavements using the M-E PDG program. The CTE data was obtained from in-service pavements in Kansas. CTE results from LTPP projects in Iowa, Kansas, and Missouri were also reviewed.

After an overview of the AASHTO TP60 test procedure and describing the hierarchical input levels used in M-E PDG, input levels 1 and 2 for CTE were presented.

For input level 1, two cores were retrieved from a PCC pavement in Kansas. The CTE values were 5.4 and 5.5 με/°F (9.8 and 9.9 με/°C). The CTE values from the LTPP database were a result of testing on 51 cores and ranged from 4 to 7.1 με/°F (7.2 to 12.8 με/°C). The lowest 10% (4.3 με/°F or 7.8 με/°C) and highest 10% (6.5 με/°F or 11.7 με/°C) mean values were used in the sensitivity analyses in this study. The CTE values for Iowa retrieved from LTPP database ranged from 4.4 to 7.6 με/°F (8.0 to 13.8 με/°C) based on 62 cores. Also, the CTE values for Missouri were between 4.1 and 11.0 με/°F (7.3 and 19.8 με/°C).

Level 2 CTE values were calculated from an equation suggested by M-E PDG. The values needed for the calculation were extracted from the LTPP database. For Kansas aggregates, CTE of dolomite, gravel, limestone, and sandstone were calculated and compared to measured values (Figure 2-9). The calculated CTE values were 11 to 19% higher than the measured values. For Iowa, dolomite and limestone CTE values were calculated. The calculated values were 10 to 14% higher than the measured ones (Figure 2-10). The aggregates available in Missouri were dolomite, limestone, a combination of dolomite and limestone, and sandstone. The calculated values, except for dolomite, were 13 to 30% higher than the measured values (Figure 2-11). For dolomite, the discrepancy between the calculated and measured values was 25%.

In the same study, in order to investigate the effect of CTE on PCC pavement performance, six in-service jointed plain concrete pavement projects were selected. Three levels of CTE (average of the highest 10% based on LTPP data, CTE based on a recently built project, and average of the lowest 10% based on LTPP data) were used in the M-E PDG design analysis.

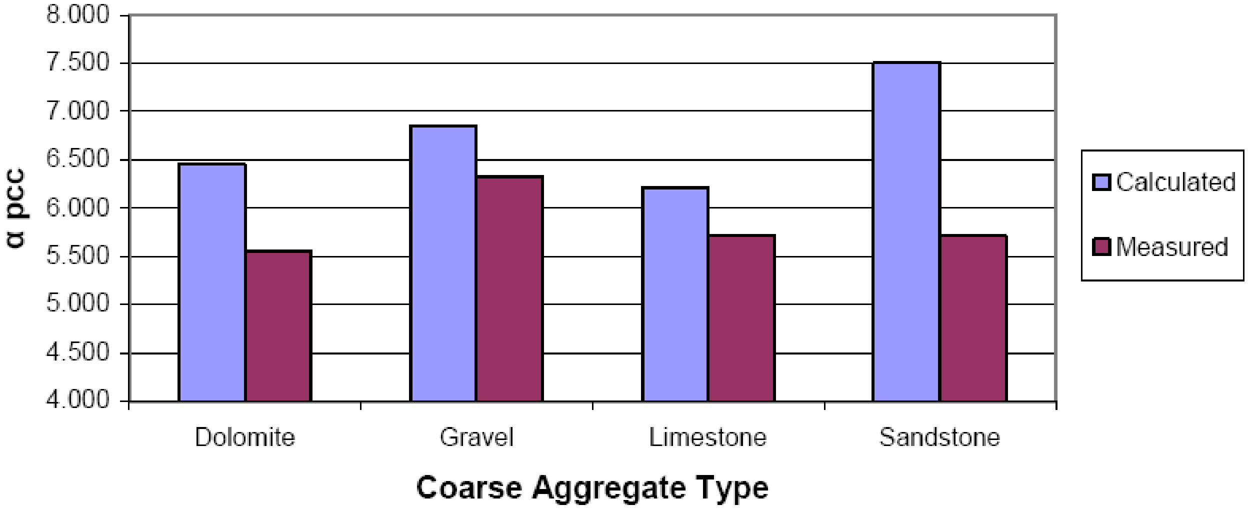


Figure 2-9. Calculated and Measured PCC CTE Values (x 10-6/ºF) for Kansas *(5)*

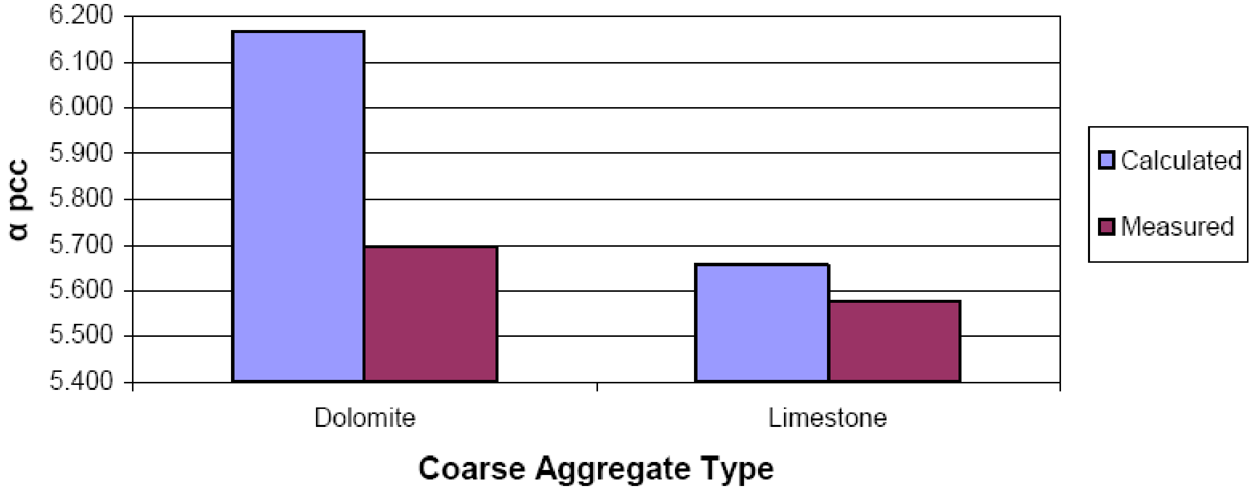


Figure 2-10. Calculated and Measured PCC CTE Values (x 10-6/ºF) for Iowa *(5)*

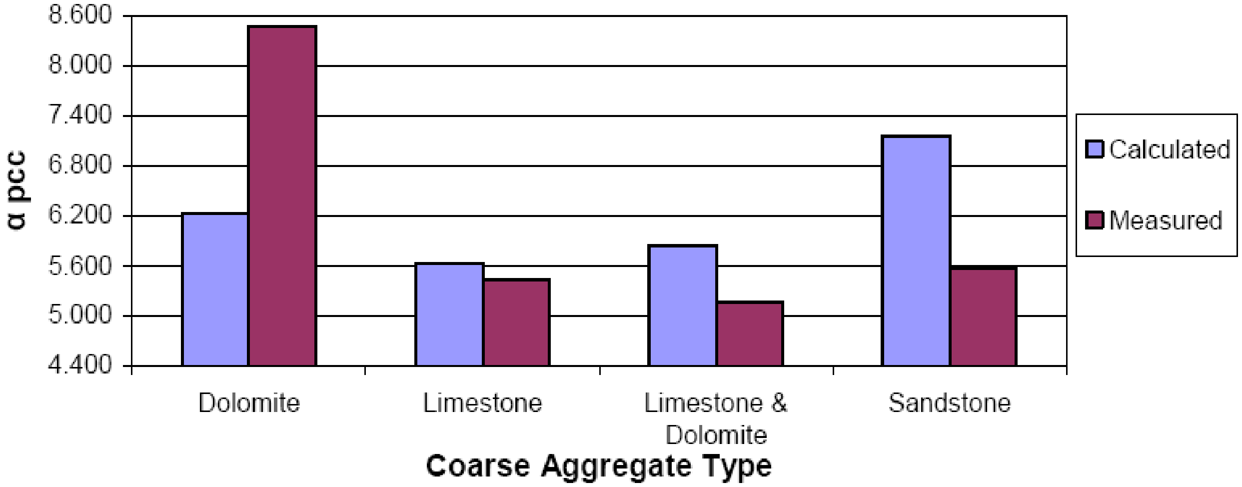


Figure 2-11. Calculated and Measured PCC CTE Values (x 10-6/ºF) for Missouri *(5)*

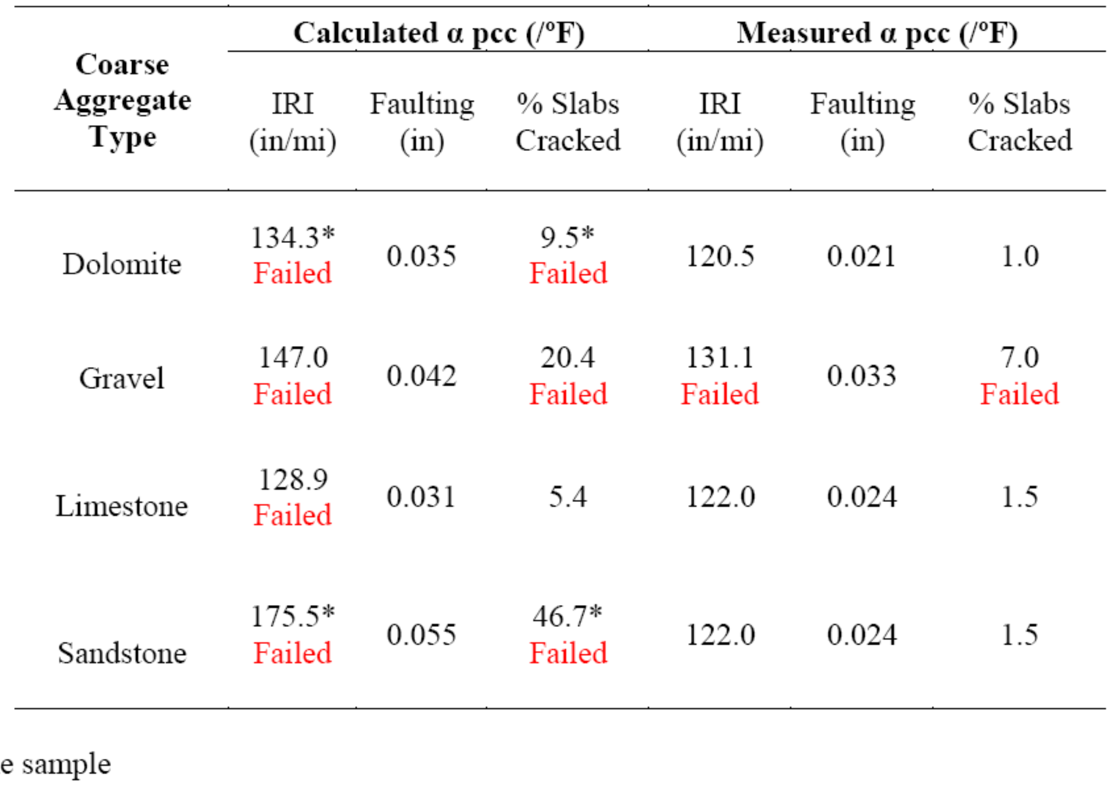
The effect of CTE on IRI is that higher CTE would result in higher IRI. For example with an increase in CTE from 4.3 to 6.5 με/°F (7.8 to 11.7 με/°C), IRI increased from 114 to 135 inch/mile. By studying other pavements, it appeared the effect of CTE on IRI is more pronounced in pavements with thinner slabs or lower strength. It was also found that the CTE does not affect the predicted IRI for pavements with widened lanes and tied PCC shoulders.

Faulting was found to be sensitive to CTE values. A combination of high cement factor and higher CTE values would result in higher faulting.

The effect of CTE on percent slabs cracked was found to be very significant. For example, with a CTE value of 4.3 με/°F (7.8 με/°C), the percent slabs cracked was 0.2% while for a CTE value of 6.5 με/°F (11.7 με/°C), the percentage increased to 2% which is a tenfold increase for a 50% increase in the CTE value.

Another part of the study was to investigate the hierarchical input levels on PCC performance. For this purpose, one project was selected. Four types of coarse aggregates (dolomite, limestone, gravel, and sandstone) were studied. Level 1 (measured) and level 2 (calculated) inputs were investigated. Table 2-1 shows the results. The design using calculated CTE values failed (based on design reliability of 90%) for IRI and/or percent slabs cracked for all aggregate types and for gravel with measured CTE value. Faulting was relatively unaffected for all aggregate types and both input levels. *(5)*

Table 2-1. Predicted Distresses for Computed and Measured PCC CTE Values for Typical Aggregates in Kansas *(5)*



Coarse Aggregate Type	Calculated α pcc (/°F)			Measured α pcc (/°F)		
	IRI (in/mi)	Faulting (in)	% Slabs Cracked	IRI (in/mi)	Faulting (in)	% Slabs Cracked
Dolomite	134.3* Failed	0.035	9.5* Failed	120.5	0.021	1.0
Gravel	147.0 Failed	0.042	20.4 Failed	131.1 Failed	0.033	7.0 Failed
Limestone	128.9 Failed	0.031	5.4	122.0	0.024	1.5
Sandstone	175.5* Failed	0.055	46.7* Failed	122.0	0.024	1.5

* one sample

In a paper by Tanesi, et al. the effect of CTE variability on concrete pavement performance was investigated *(6)*. The AASHTO TP60 method was described and possible sources of CTE variability were mentioned. Specimen induced variability (moisture state and temperature gradient within the concrete specimen, specimen inhomogeneities) and equipment induced variability (LVDT sensitivity, power fluctuations, and frame calibration) as well as the intrinsic equipment limitations were mentioned as possible sources of variability among CTE values.

Since 1996 the Federal Highway Administration (FHWA) has tested over 1800 core samples from various LTPP sections throughout the country. The CTE values ranged from 4.5 με/°F to 7.5 με/°F (8.1 με/°C to 13.5 με/°C) as shown in Figure 2-12. Approximately 150 specimens were tested multiple times to determine the repeatability of the test procedure. The average variability amongst replicate samples was reported to be 0.4 με/°F (0.72 με/°C) as presented in Figure 2-13. δCTE is the maximum difference between CTE test results performed on the same specimen.

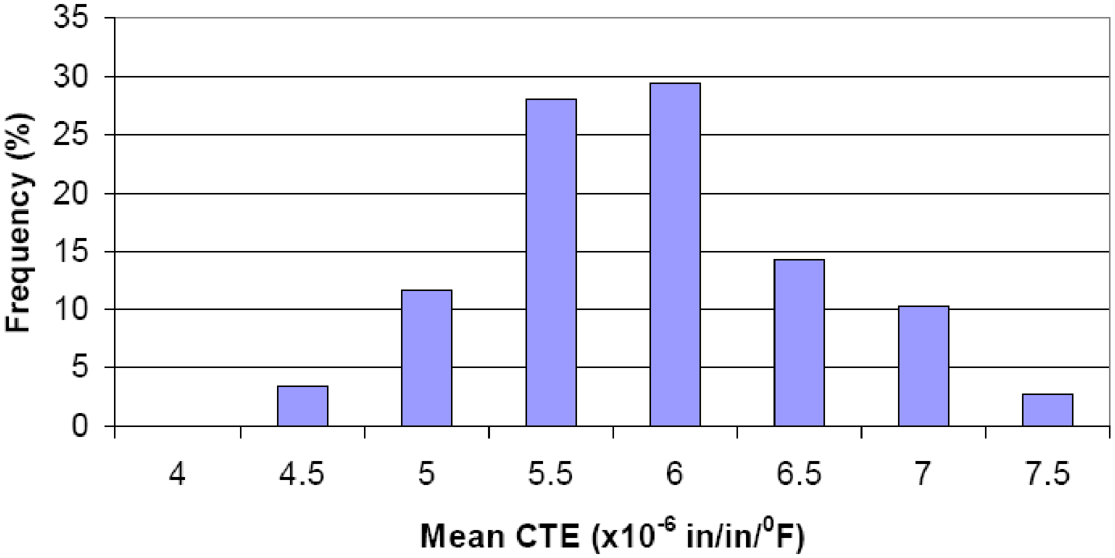


Figure 2-12. Histogram of the Mean CTE of the Specimens *(6)*

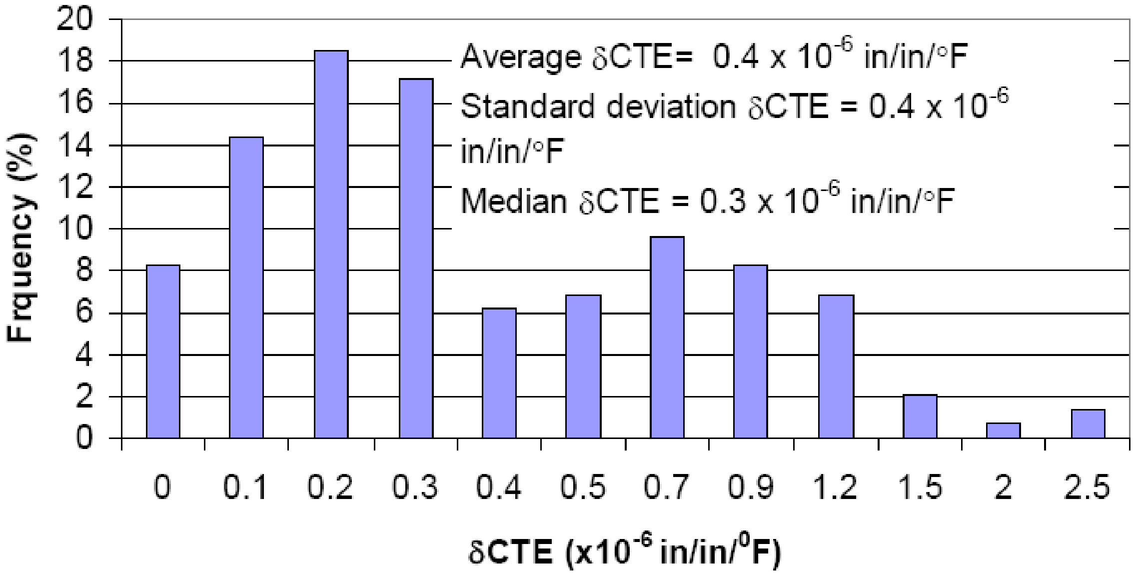


Figure 2-13. Histogram of the δCTE *(6)*

The impact of variability on the predicted performance of concrete pavements was also documented in this paper. Based on sensitivity analysis using M-E PDG program the effect of the CTE variability on slab cracking was found to be significant. The higher the CTE, the greater the effect of variability. As an example, a difference of 2.0 με/^{o}F (3.6 με/^{o}C) between minimum and maximum measured CTE values for the same specimen with an average CTE value of 4.0 με/^{o}F (7.2 με/^{o}C) would result in 8% difference in the predicted percent of slabs cracked, but the difference would be 65% if the average CTE value were 6.5 με/^{o}F (11.7 με/^{o}C). Figure 2-14 shows the effect of CTE variability on predicted percent slabs cracked. dCTE in Figures 2-14, through 2-16 is the same as δCTE.

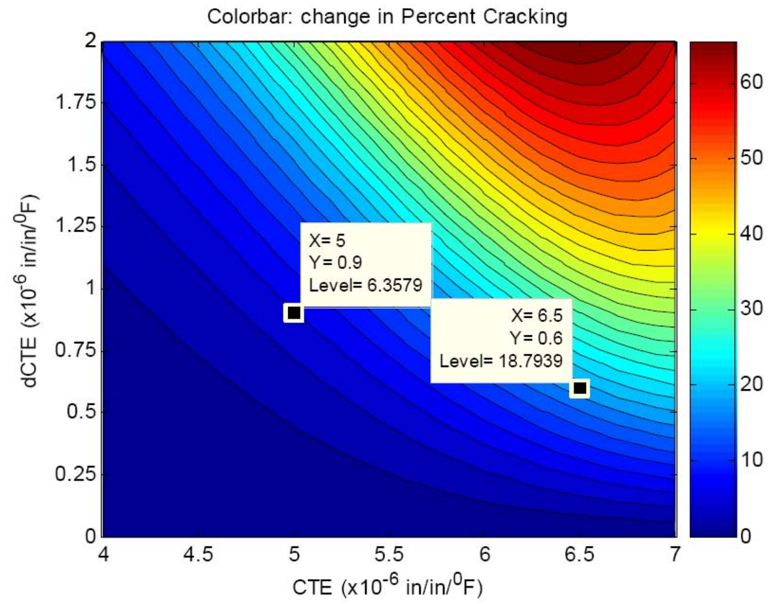


Figure 2-14. Difference in the Predicted Percent Slabs Cracked as a Result of the dCTE *(6)*

The same effect mentioned above can be seen on the predicted faulting of concrete pavements as shown in Figure 2-15.

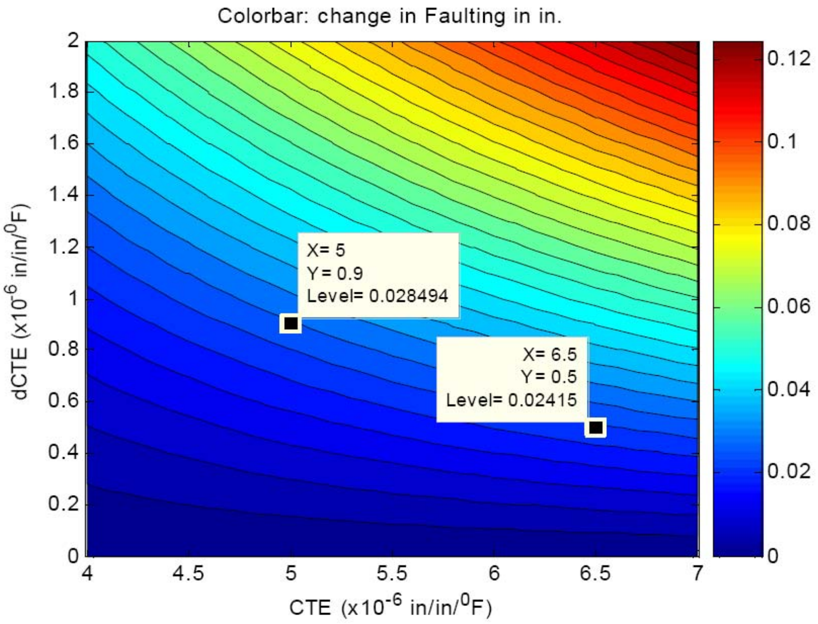


Figure 2-15. Difference in the Predicted Faulting as a Result of the dCTE *(6)*

The impact of δCTE on the International Roughness Index (IRI) was also documented. The effect is similar to the one of the percent slabs cracked case. For the same example mentioned above, the IRI for the first case (a difference of 2.0 με/°F or 3.6 με/°C for a specimen with average CTE value of 4.0 με/°F or 7.2 με/°C) the difference in IRI is 33 inch/mile, while for the second case it is 113 inch/mile. Figure 2-16 illustrates this effect.

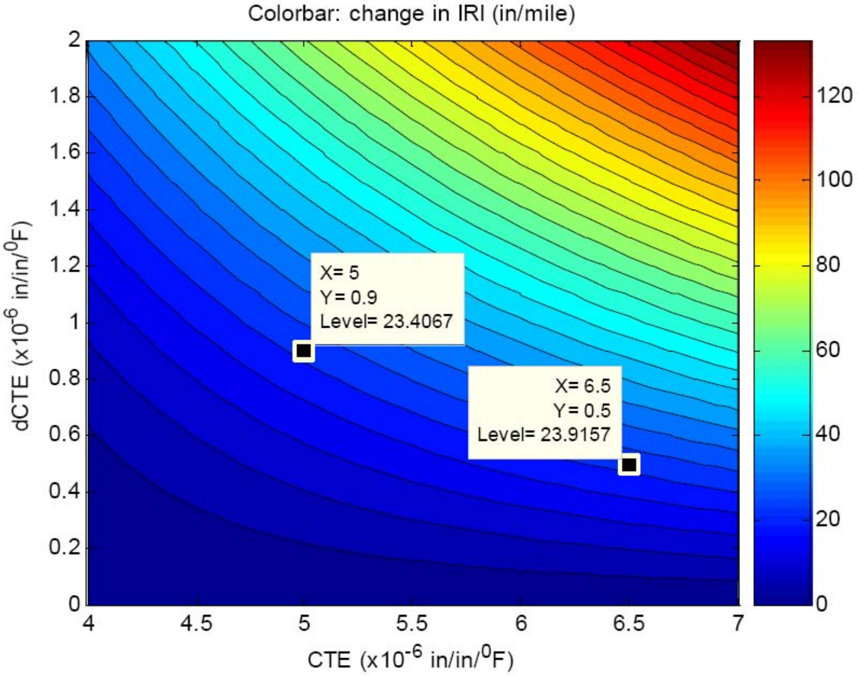


Figure 2-16. Difference in the Predicted IRI as a Result of the dCTE *(6)*

The authors concluded that the CTE test variability leads to significant discrepancies in the predicted IRI, percent slabs cracked, and faulting. *(6)*

Kohler, Alvarado and Jones *(7)* at the University of California Davis qualitatively investigated the effects of aggregate geology, number of thermal cycles and soaking time on the magnitude of CTE. The CTE test was conducted on 74 core samples obtained from four regions within the state of California. The testing was done in accordance with the revised AASHTO TP60 protocol proposed by Moon Won *(3)*. The overall range of CTE was between 4.5 and 6.7 με/°F (8.10 and 12.06 με/°C).

In order to study the effect of the number of heating-cooling cycles, 74 cores were analyzed. Samples were subjected to three heating-cooling cycles. It was found that the third cycle produced better coefficient of determination (R^2) values for the regression analysis used to calculate CTE values and that the difference between heating and cooling cycles was reduced in the third cycle. Also, in 76% of the cases, the third cycle resulted in lower CTE values than the first cycle values. The CTE of the third cycle was found to be on average 0.15 με/°F (0.27 με/°C) lower than the first cycle CTE value. Figure 2-17 shows the effect of repeated thermal cycles on R^2 and CTE values. It was stated that this improvement in R^2 value and the difference between heating-cooling cycles improved the confidence in the results and it was an indication that the concrete had reached a stable condition regarding pore water.

To quantify the effect of concrete saturation on CTE value, three cores were oven-dried overnight. Two of the cores were tested for CTE immediately after air cooling, and the third one was soaked for 96 hours. The dry cores showed a reduction of the difference between heating and cooling cycles during the first 10 to 15 hours (Figure 2-18). The saturated core showed a constant CTE value for heating and cooling cycles during the 9 cycles to which the core was subjected (Figure 2-19).

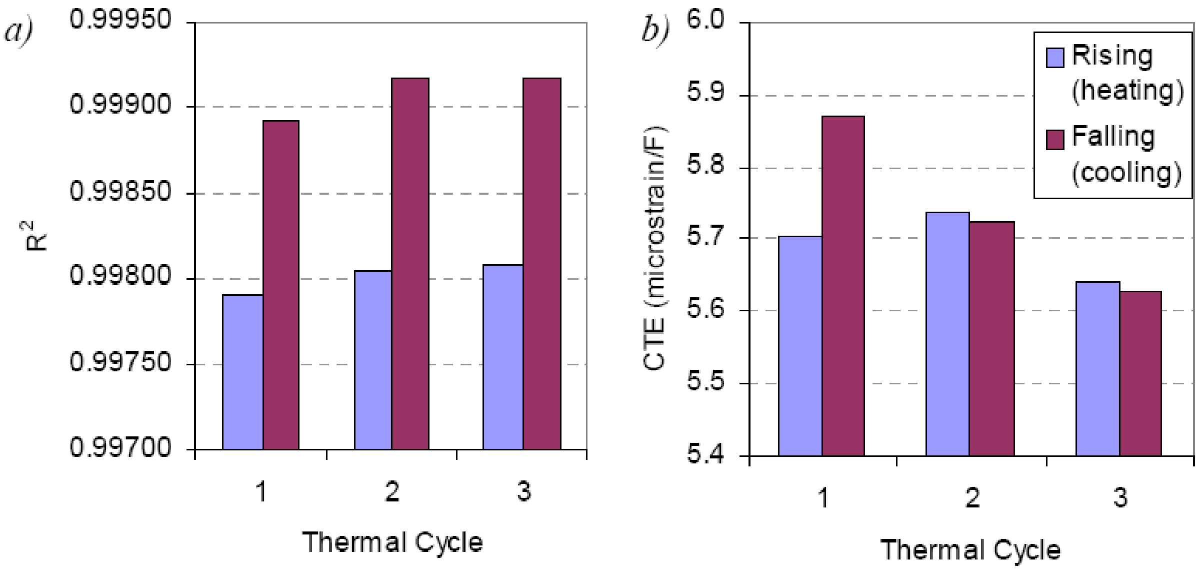


Figure 2-17. Effect of Repeated Thermal Cycles on CTE, (a) Increase in R^2, (b) Decrease in CTE *(7)*

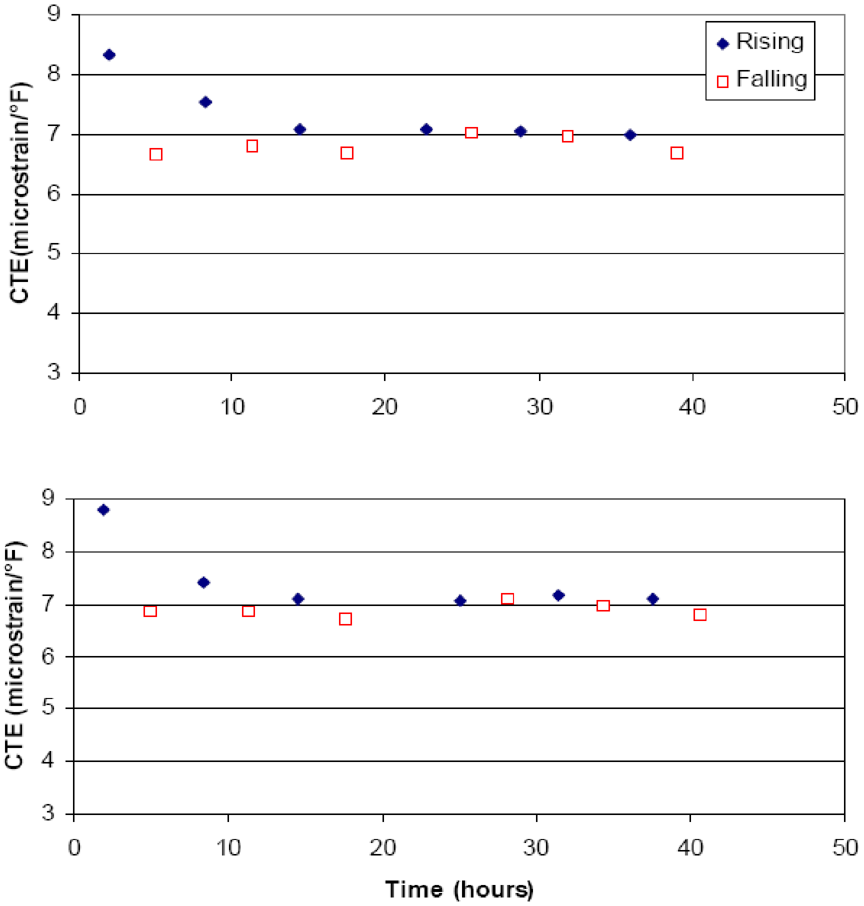


Figure 2-18. Effect of Saturation on CTE on Two Oven-Dried Cores *(7)*

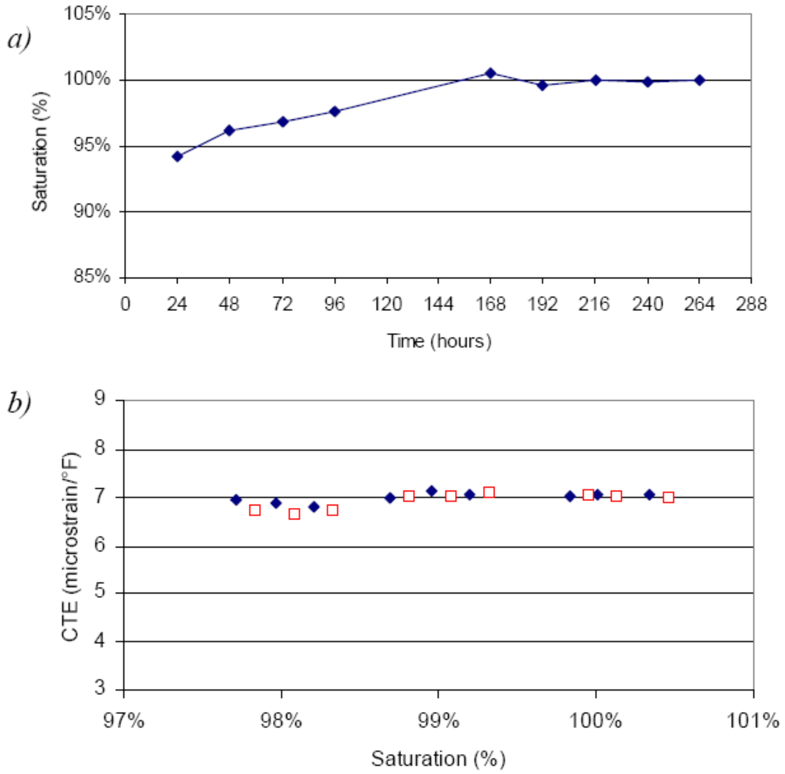


Figure 2-19. CTE Variability at High Saturation Levels *(7)*

The geographical variability was assessed by testing cores from four California Department of Transportation districts. Northern area (District 2) aggregates were probably sourced from alluvial or glacial deposits. A mix of sandstone and basalt rocks was evident. Southern area (District 11) aggregates were predominantly granitic. Coastal area (District 4) and valley area (District 10) aggregates were predominantly sandstone. The average CTE of District 2 was 6.3 με/°F (11.34 με/°C), for District 11 the average was 5.5 με/°F (9.90 με/°C), District 4 had an average CTE value of 5.2 με/°F (9.36 με/°C), and the average CTE value of the District 10 was 6.4 με/°F (11.52 με/°C). Table 2-2 shows the CTE values at different sites. It was concluded that the geographical variability is probably associated with variability in aggregates of different mineralogical composition. *(7)*

Table 2-2. Mean, Maximum, and Minimum CTE at Different Sites *(7)*

District	Site	Postmiles	Nr.of cores	Mean CTE (ε/°F·10^{-6})	Min/Max CTE (ε/°F·10^{-6})	Range
4	SCL-85-N	13.90-15.17	6	5.22	4.73 / 5.68	0.95
4	SCL-85-S	13.52-15.52	12	5.08	4.46 / 6.07	1.61
4	SOL-80-E	18.46-34.34	12	5.38	4.63 / 6.24	1.61
4	SON-101-N	50.52-51.79	5	5.14	4.50 / 5.60	1.10
4	SON-101-S	50.84-53.02	7	5.18	4.80 / 5.62	0.82
10	SJ-580-E	5.02-8.88	10	6.35	6.12 / 6.57	0.45
10	SJ-580-W	5.35-8.70	9	6.48	6.21 / 6.69	0.48
2	SHA-5-N	37.85-39.91	6	6.29	6.23 / 6.39	0.16
2	SHA-5-S	29.53-31.71	3	6.28	5.96 / 6.69	0.73
11	IMP-86-S	23.50-29.56	4	5.48	5.43 / 5.53	0.10

Kohler and Kannekanti *(8)* studied the influence of PCC CTE on the cracking of the JPCP. One hundred and four in-service highway sections in California were selected for this study and cores obtained from these sections were tested in the University of California pavement research center laboratory.

The CTE testing protocol followed in the University of California study was based on the recommended amendments to the AASHTO TP60 protocol proposed by Moon Won *(3)*. The main features of this testing procedure are summarized in this paper. The CTE of each section was generally determined from the CTE results of at least two cores. Total number of tested cores was 185. The CTE values ranged from 5.1 to 6.7 $\mu\varepsilon/^{o}$F (9.1 to 12.0 $\mu\varepsilon/^{o}$C).

Three types of cracking levels were included in the data collected by California Department of Transportation. First stage cracks (FSC) are cracks that do not intersect and divide the slab into two or more large pieces; third stage cracks (TSC) are interconnected cracks that divide the slab into three or more large pieces; corner cracks (CC) are diagonal cracks that meet both longitudinal and transverse joint within 6 feet and over 2 feet at the same slab corner. Figure 2-20 shows examples of these crack levels. Slab cracking is reported as a percentage based on the number of slabs exhibiting these cracking levels over the surveyed distance (0.1 to 1.5 miles for a given homogeneous section). Ratio of the severely cracked sections to total number of sections was calculated. The severity limit used for FSC and TSC was 10% and for CC, 5% limit was used.

Figure 2-20. Examples of FSC, TSC, and CC *(8)*

The ratio of cracked slabs mentioned above was computed using a CTE limit value (5.7 $\mu\varepsilon/^{o}$F or 10.26 $\mu\varepsilon/^{o}$C) to separate the data for slabs with low and high CTE values. This ratio versus pavement age in years was then plotted (Figure 2-21). It was seen that the cracking trends for low and high CTE pavements were drastically different. For all types of cracks, pavements with high CTE developed more cracks over time than the pavements with low CTE. It was concluded that if low CTE is specified, it can reduce cracking over the life of JPCP and longer lasting concrete pavements can be expected. *(8)*

2.3 Literature on Various Test Methods to Determine CTE

In a paper by Loubser and Bryden *(9)*, an apparatus for determining CTE of concrete is described. The apparatus consists of an oven, an aluminum fixture, a fused silica tube, an LVDT, and thermocouples. The minimum size of specimens was fixed at 4*0.8*0.8 in. The moisture condition of the specimens tested varied from oven-dried to saturated. The length change of the specimen over the temperature range (68 to 176 ^{o}F or 20 to 80 ^{o}C) was measured and the CTE was calculated accordingly. *(9)*

The test method developed by Army Corps of Engineers *(10)* uses a heating and cooling bath, length comparator, reference bars, and inserts. It was stated that the CTE of concrete varies with different moisture conditions being minimum at saturated or oven dry conditions and maximum at about 70% saturation. Therefore, it is important to specify the relevant moisture condition (oven dry, saturated, or partially saturated) before conducting the test. This test method calculates the CTE of concrete by determination of length change due to temperature change over a range of 41 to 140 ^{o}F (5 to 60 ^{o}C). *(10)*

The Danish standard (1994) method *(11)* uses a measuring device for length change, thermocouples, and three water baths to measure the CTE of concrete at three temperatures (5, 20, and 30 °C). The specimens are concrete prisms of 4*4*14 in. The measured CTE is then corrected by considering the temperature sensitivity of the measuring device and the shrinkage of the concrete. *(11)*

A method of measuring the CTE of ultra-high strength reactive powder concrete (RPC) is reported by Childs, Wong, Gowripalan, and Peng at the University of New South Wales, Australia. This method uses fiber optic sensors to measure the CTE of concrete. *(12)*

InstroTek has developed a test method and device for CTE determination under a contract with FHWA that uses non-contact laser for length change measurements. Heating, cooling, and height measurements are controlled automatically. Height measurements are accomplished by a laser traveling across the top of one or two samples immersed in a temperature controlled water bath. The measurements over the sample surface are taken and averaged for each sample at a given temperature. CTE values are then automatically calculated and displayed once the test cycle is completed. *(13)*

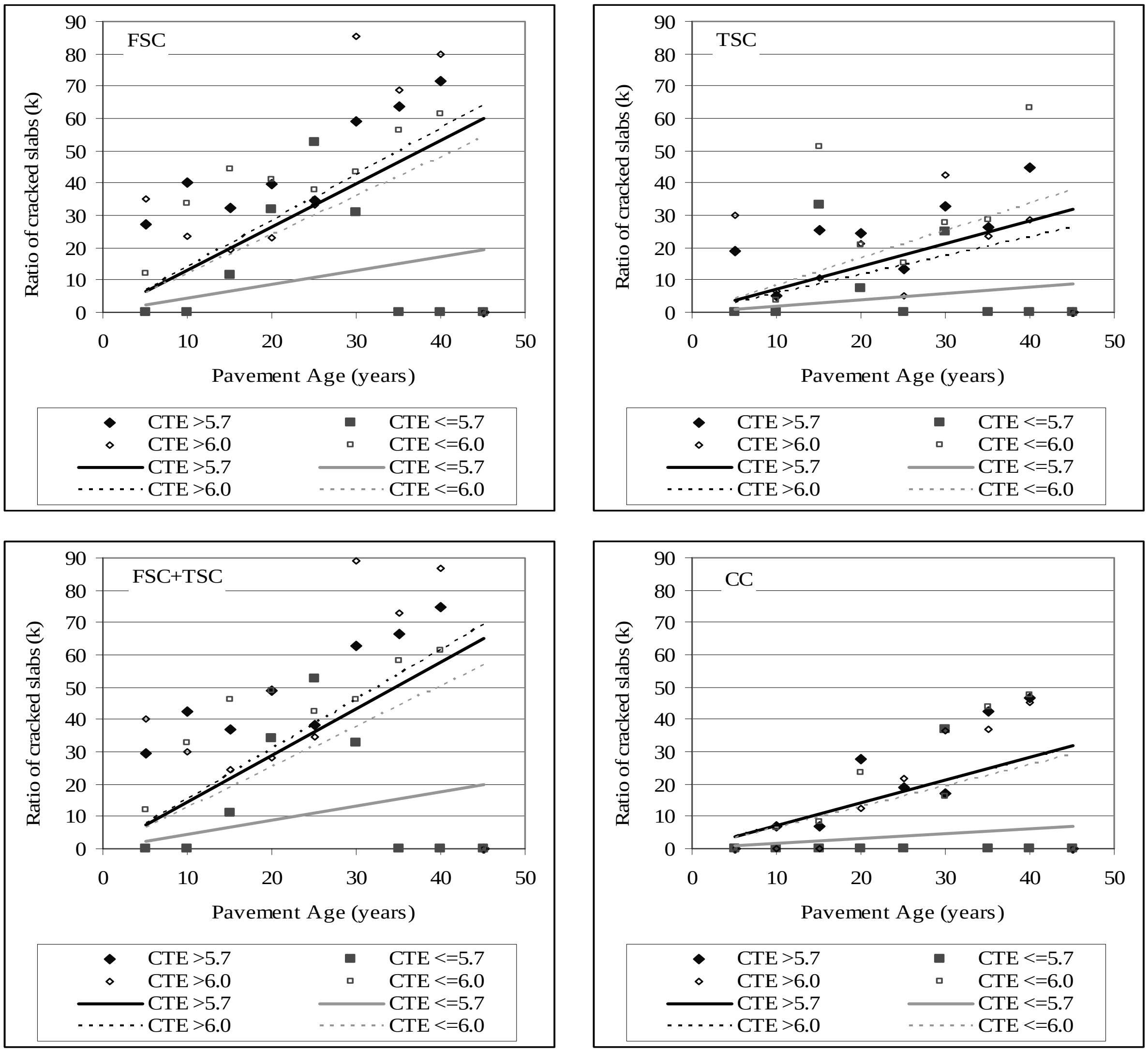


Figure 2-21. Comparison of Ratio of Cracked Slabs for Cases for Pavements with High and Low CTE (Arbitrary Limits at CTE=5.7 με/°F or 10.26 με/°C and Alternatively at CTE=6.0 με/°F or 10.8 με/°C) ***(8)***

2.4 State-of-the-Practice Survey Results

As part of the literature review, the authors also documented the process followed by various state DOTs. The survey instrument presented in Table 2-3 was sent to 50 state DOTs. Table A-1 of Appendix A summarizes the responses received from 17 state DOTs. Based on survey results, as of July 2006, only four states (AL, KS, TX, and UT) have initiated studies to document CTE for pavement design.

Table 2-3. Survey Instrument

Use this form to participate in a survey of Coefficient of Thermal Expansion (CTE) practices currently used by State Highway Agencies in the United States. This survey is being conducted as part of a Michigan Department of Transportation study titled "Quantifying Coefficient of Thermal Expansion Values of Typical Hydraulic Cement Concrete Paving Mixtures."

Participant Details	
Name	
Title	
Organization	
Phone Number	
Fax Number	
Email address	

CTE Testing Practices	
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"	
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): *ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc.*	
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?	
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?	
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	

Responses requested by June 30, 2006. Please send the completed survey to Dr. Neeraj Buch (Principal Investigator). The email address is buch@egr.msu.edu. Alternatively the completed survey can be faxed to 517-432-0012.

Thank you for participating in the survey.

CHAPTER 3: DESCRIPTION OF THE EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter provides details regarding the materials used in the fabrication of the test specimens, the tests used for determining fresh and hardened concrete properties, and the CTE test protocols.

3.2 Materials, Fresh and Hardened Concrete Properties Tests

The concrete used in the fabrication of cylindrical and prismatic test specimens was supplied by a local ready mix supplier. This ensured that all specimens needed for a given mixture were produced from a single batch, thereby reducing experiment variability. The coarse aggregate sources are presented in Table 3-1. Figure 3-1 shows the locations of the various aggregate sources within the state of Michigan. Mineralogical composition and physical properties are summarized in Tables 3-2 through 3-4.

Table 3-1. Coarse Aggregate Types and Source Names

Mix ID	Primary Agg. Class	Agg. Source, County
CTE 1	Limestone	Pit # 71-47, Presque Isle
CTE 2	Gravel	Pit # 19-56, Clinton
CTE 3	Limestone	Pit # 75-5, Schoolcraft
CTE 4	Slag	Pit # 82-19, Wayne
CTE 5	Dolomite	Pit # 49-65, Mackinac
CTE 6	Gabbro	Pit # 95-10, Ontario
CTE 7	Dolomite	Pit # 58-11, Monroe
CTE 8	Dolomite	Pit # 91-06, Cook

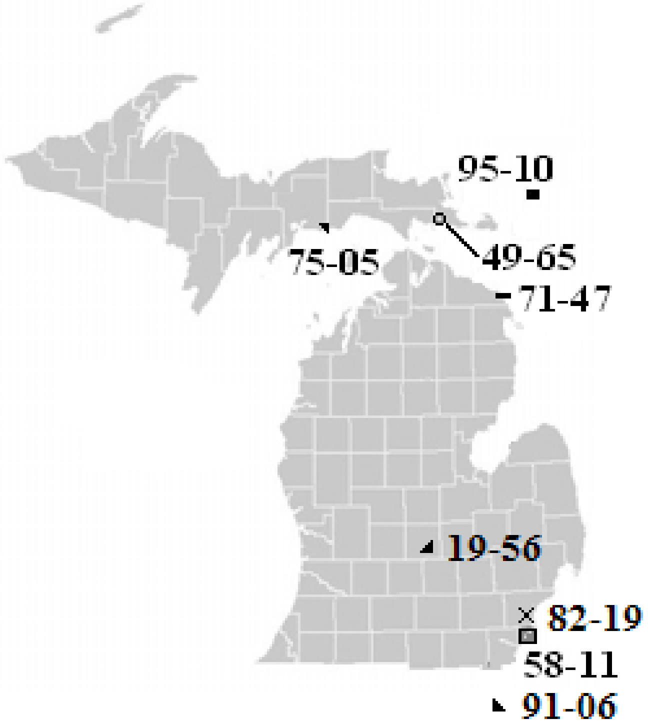


Figure 3-1. Locations of Some of the Aggregate Sources *(After 14)*

Table 3-2. Mineralogical and Physical Properties of the Coarse Aggregate *(14)*

Mix ID	Primary Rock Type	Mineral % by Weight				Description	Specific Gravity, Oven Dry	Absorption Capacity
		Ca-Mg$(CO_3)_2$	$CaCO_3$	FeS_2	Other			
CTE 1	Limestone	4.58	94.33	0.14	0.54	Tan to brown, to dark brown with abundant fossils in a fine grained limestone matrix	2.575	1.14
CTE 2	Gravel	*				N/A	2.571	2.70
CTE 3	Limestone	7.27	90.79	0.06	0.94	Light tan to tan fine grained limestone	2.649	0.69
CTE 4	Slag	*				The vesicular particles are grey, the dense particles are grey to tan or brown, the glassy particles show yellowish to black vitreous exposure	2.329	2.78
CTE 5	Dolomite	98.14	0.48	0.04	0.91	Light tan to gray medium to coarse grained dolomite	2.735	0.68
CTE 6	Gabbro	**				Gabbro, major phases: plagioclase, hornblende, minor phases: magnetite, quartz and apatite	2.910	0.21
CTE 7	Dolomite	95.14	0.54	0.27	2.50	Light tan to gray fine to medium grained dolomite	2.548	3.13
CTE 8	Dolomite	N/A						

* Petrographic composition is reported in Table 3-3.
** Chemical composition is reported in Table 3-4.

Table 3-3. Petrographic Composition of Slag and Gravel Aggregates*

Mix ID	Primary Rock Type	Aggregate Type	Mineral % by Weight
CTE 2	Gravel	Igneous/Metamorphic	54
		Dense Carbonates	35.4
		Absorbent Carbonates	4.7
		Non-Friable Sandstone	1.0
		Friable Sandstone	1.7
		Siltstone	0.6
		Shale + Coal	0.1
		Clay Ironstone	0.5
		Chert	2
CTE 4	Slag	Vesicular Particles	85.7
		Dense Particles	10.8
		Glassy Particles	3.3
		Magnetic Particles	0.2

* This information was provided by MDOT.

Table 3-4. Chemical Composition of Gabbro Aggregate *(14)*

Mix ID	Primary Rock Type	Oxide/Element	Oxide/Element % by Weight
CTE 6	Gabbro	MgO	8.44
		Al_2O_3	18.61
		SiO_2	45.53
		S	0.02
		CaO	11.81
		Fe_2O_3	13.13

The typical concrete mixture designs used in the fabrication of the test specimens is summarized in Table 3-5.

Table 3-5. Concrete Mixture Designs (lbs/yd^3)

Ingredients	CTE 1	CTE 2	CTE 3	CTE 4	CTE 5	CTE 6	CTE 7	CTE 8[a]
Cement	564	564	560	560	560	573	560	376
Water	259	259	250	252	275	258	242	155
Coarse Agg.	1740	1760	1838	1575	1908	1774	1715	1942
Fine Agg.	1360	1360	1338	1348	1260	1230	1330	1444
AEA, (fl. oz.)	10	10	7.5	7.5	7.5	7.5	7.5	28

[a] This mixture design also included 94 lbs/yd^3 of Fly Ash.

Concrete specimens (except for CTE 8) were prepared at the MSU Civil Infrastructure Laboratory (CIL) according to the ASTM C 192 “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory”. CTE 8 specimens were field prepared specimens from an actual paving project in Michigan. At least three replicate samples were fabricated for each test. Over 700 specimens were fabricated to characterize the mechanical properties and CTE of the concrete paving mixtures. Thermocouples were embedded in the center of designated specimens to monitor concrete temperature for the CTE tests. All specimens were de-molded after 24 hours and were cured at 100% relative humidity and 23^{o}C temperature in an environment chamber until the time of testing. CTE specimens were placed in a limewater bath as required by the test protocols. Once the specimens were de-molded and cured for an appropriate time, various tests were conducted to assess the properties of interest. The material characterization tests performed on the concrete samples are summarized in Table 3-6.

Table 3-6. Summary of Material Characterization Tests

Test Attribute	Test Name/Equipment	ASTM Designation	Measured Property	No. of Specimens	Frequency of Testing
Properties of Fresh Concrete	Slump	C 143	Concrete workability	One per batch	Not applicable
	Air content	C 231	Total air content of fresh concrete		
	Unit weight	C 138	Unit weight		
	Temperature	C 1064	Temperature		
Properties of Hardened Concrete	Compressive strength*	C 39	Concrete strength	Three replicates for each test/batch	1, 3, 7, 14, 28, 90, 365 days after specimen fabrication
	Flexural strength	C 78			
	Split tensile strength	C 496			
	Elastic modulus	C 469	Concrete stiffness		
Thermal Property	Coefficient of thermal expansion	AASHTO TP60	Linear length change/unit change in temperature		3, 7, 14, 28, 90, 180, 365 days after specimen fabrication

* Compressive strength was determined by the same apparatus and specimen used to determine the modulus of elasticity.

3.3 Thermal Property Test (Coefficient of Thermal Expansion Test)

CTE test was conducted according to the AASHTO TP60 “Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete”. The CTE test apparatus consists of a (i) temperature controlled water bath; (ii) rigid frame to support the test specimen; (iii) LVDT to record the change in specimen length; and (iv) data acquisition system for continuous data collection. Figures 3-2a and 3-2b illustrate the CTE test setup.

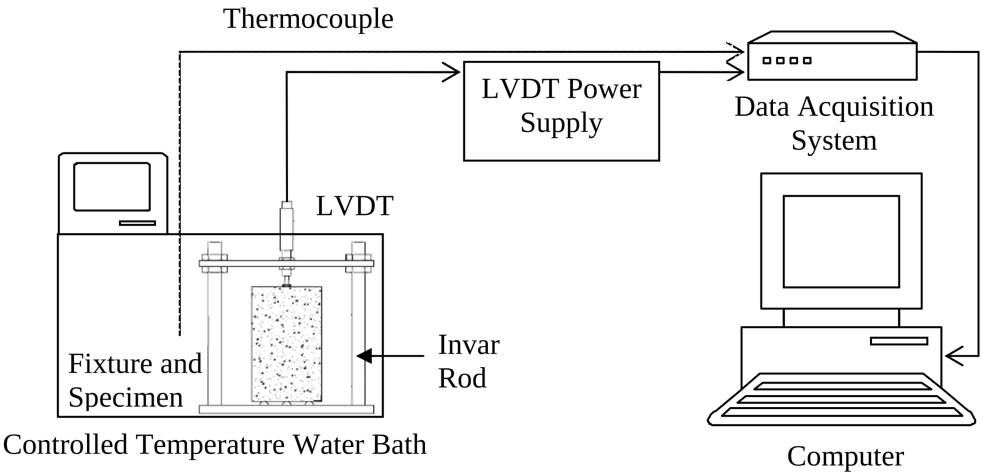


Figure 3-2a. Schematic of the Test Setup

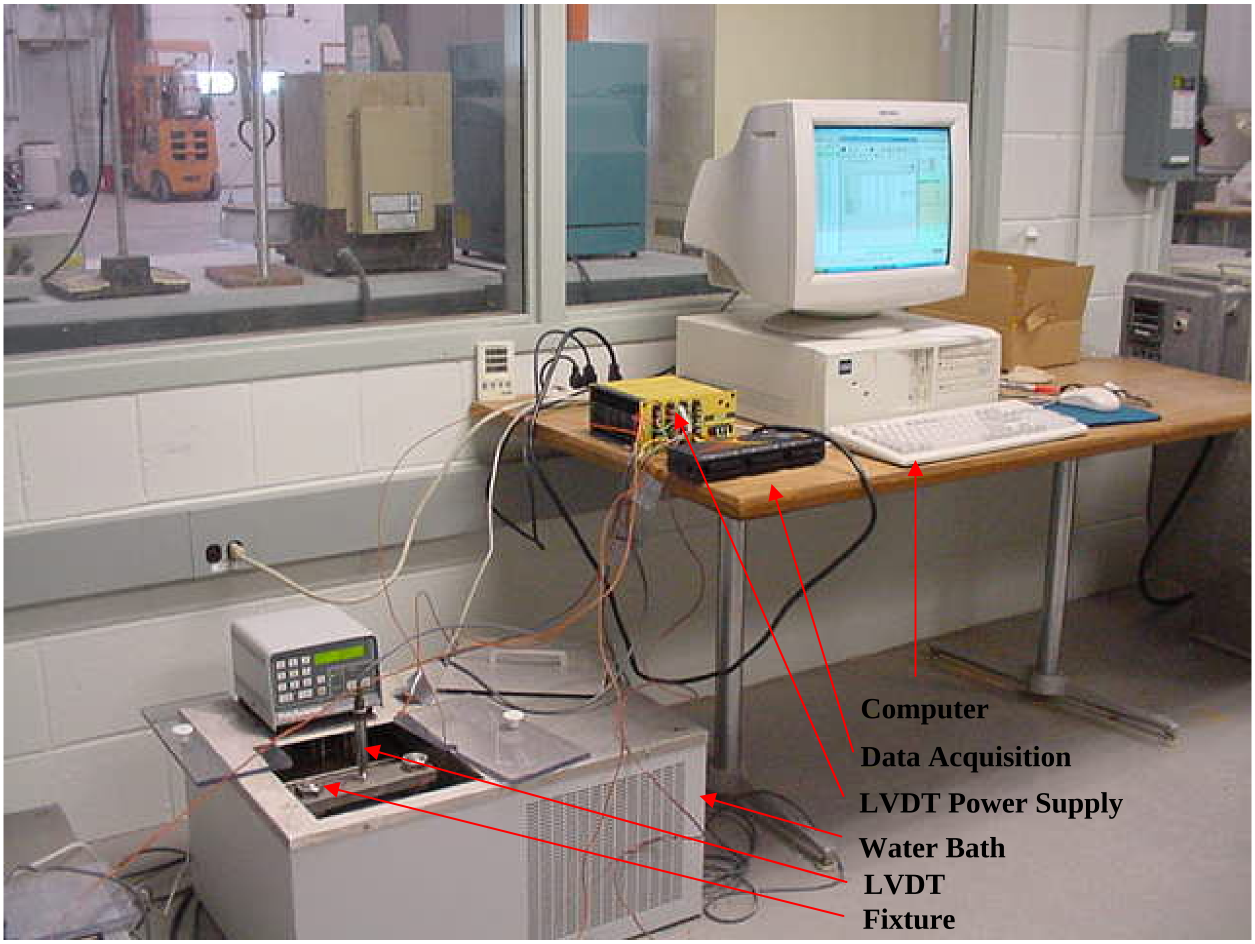


Figure 3-2b. Complete Test Setup

3.3.1 Controlled Temperature Water Bath

Three “PolyScience” Programmable Refrigerating/Heating Circulators were used in this experiment. The temperature range for these circulators is -25 to +150°C with temperature stability of ±0.01 °C. Figure 3-3 shows a Model 9612 circulator.

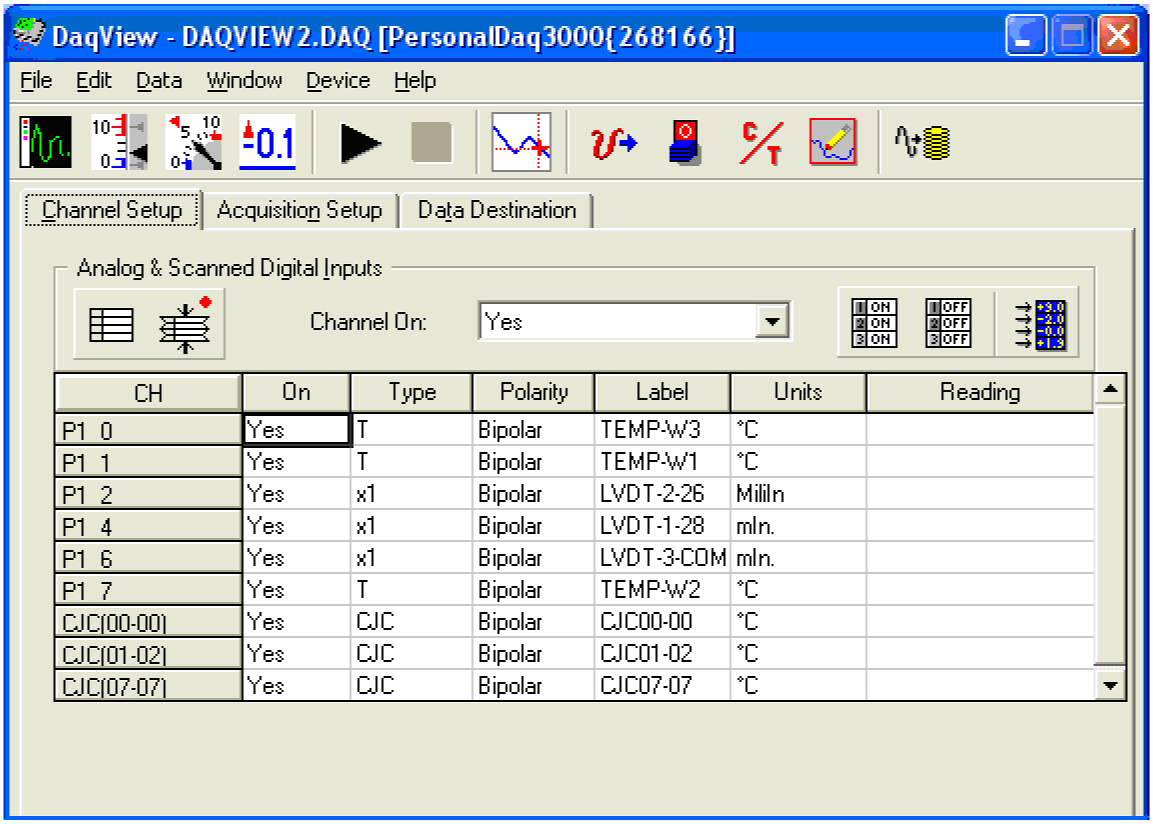
Figure 3-3. Controlled Temperature Water Bath *(15)*

3.3.2 Data Acquisition System

An “IOtech” Personal Daq/3000 data acquisition system was used to read and record the length changes of the specimens through LVDTs and record water bath temperatures. This system has eight analog inputs. The data acquisition system is shown in Figure 3-4.

Figure 3-4. Data Acquisition System *(16)*

The software used with this system was DaqView™ which allows the user to save the data in text format among other file formats. A screen shot of the channel setup is illustrated in Figure 3-5.



Channel On: Yes

CH	On	Type	Polarity	Label	Units	Reading
P1 0	Yes	T	Bipolar	TEMP-W3	°C	
P1 1	Yes	T	Bipolar	TEMP-W1	°C	
P1 2	Yes	x1	Bipolar	LVDT-2-26	MiliIn	
P1 4	Yes	x1	Bipolar	LVDT-1-28	mIn.	
P1 6	Yes	x1	Bipolar	LVDT-3-COM	mIn.	
P1 7	Yes	T	Bipolar	TEMP-W2	°C	
CJC(00-00)	Yes	CJC	Bipolar	CJC00-00	°C	
CJC(01-02)	Yes	CJC	Bipolar	CJC01-02	°C	
CJC(07-07)	Yes	CJC	Bipolar	CJC07-07	°C	

Figure 3-5. DaqView™ Software Channel Setup Screen

3.3.3 Linear Variable Differential Transformer (LVDT)

Three “Macro Sensors” GHSD 750-050 Spring-Loaded DC-LVDT Position Sensors were used to measure the length changes of concrete specimens subjected to temperature cycles. These LVDTs have a nominal range of ±0.050 in. from null position and full scale output of 0 to ±10 V DC. Figure 3-6 shows the LVDTs.

Figure 3-6. Spring-Loaded LVDTs *(17)*

3.3.4 Rigid Support Frame

Rigid support frames were fabricated based on AASHTO TP60 appendix X.1 “Specimen Measuring Apparatus”. Figure 3-7 shows the rigid support frame. The circular base plate is made of Aluminum and has a diameter of 10 inches. Three semi-spherical support buttons equally spaced around a 2 inch diameter circle are placed on the base plate. The frame height is 10 inches and the vertical rods are made of Invar (a nickel-iron alloy with very low CTE) in order to minimize the effect of frame length changes on the measurements. The side view and plan view of the rigid support frame are shown in Figure 3-8.

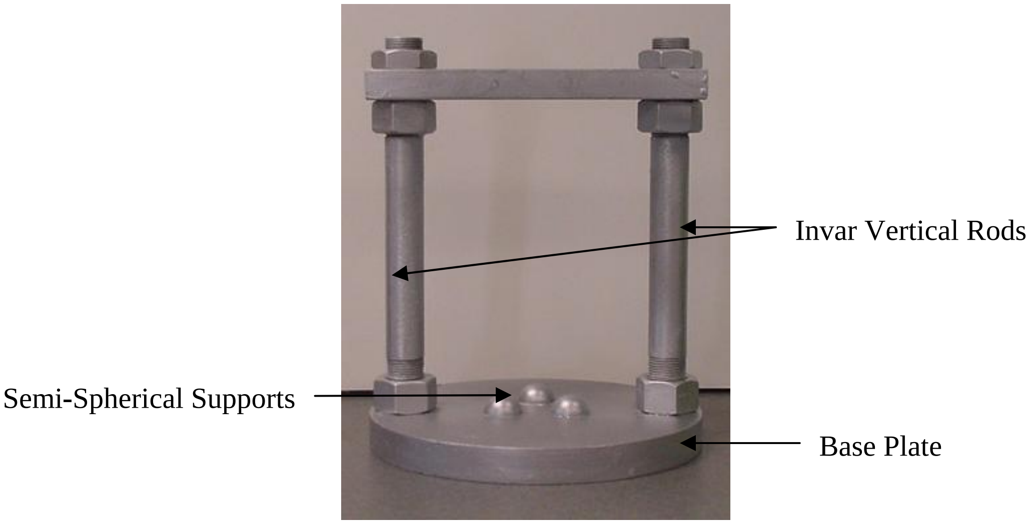


Figure 3-7. Rigid Support Frame

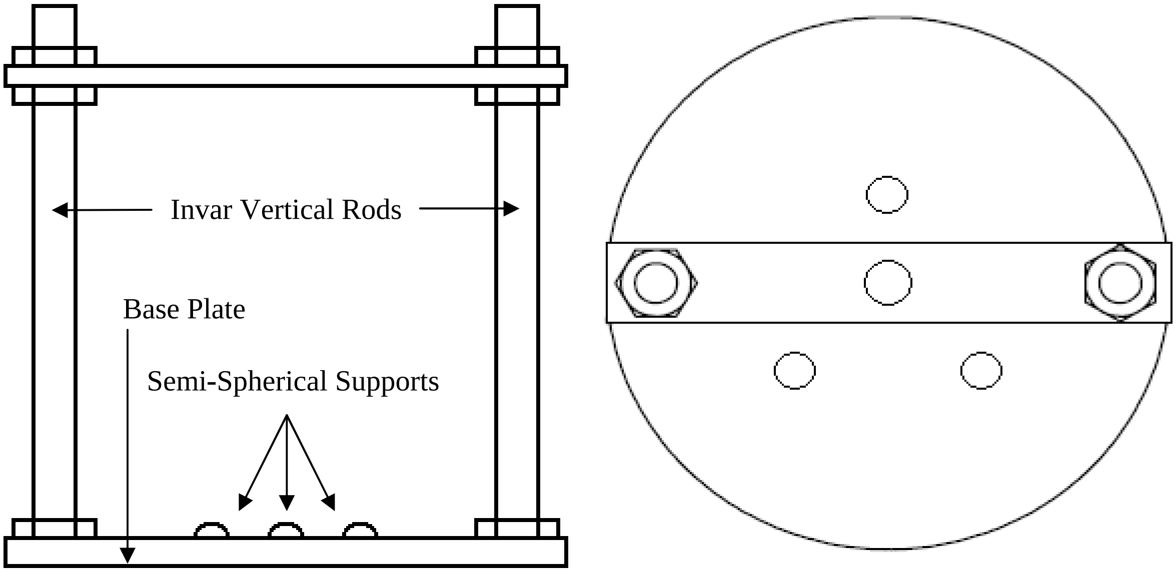


Figure 3-8. Side View and Plan View of the Rigid Support Frame *(After 18)*

3.3.5 Test Procedure and Data Collection

Specimens were subjected to at least three heating-cooling cycles (Figure 3-9). This way, if one cycle was not suitable for CTE calculations due to problems with test conditions (specimen and LVDT misalignment, lack of proper seating of the specimen, etc.), the replicate cycles could be used for CTE calculations.

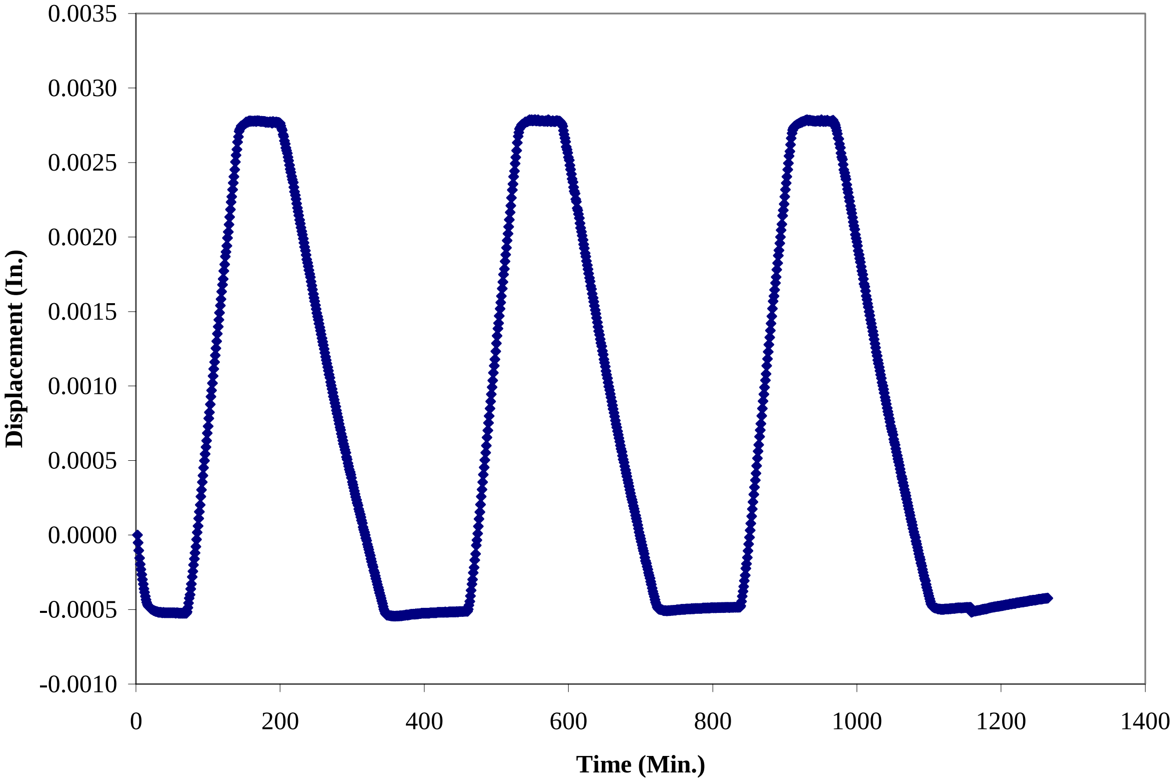


Figure 3-9. Three Typical Heating-Cooling Cycles

A thermocouple was inserted in each bath to record the water temperature. Thermocouples were also embedded in the concrete samples to monitor the specimen temperature during the CTE test. It was found that both the specimen and water follow similar temperature signature, however, the concrete specimen lags the water temperature by approximately 10 minutes. Figure 3.10 shows a typical temperature graph.

Temperature and displacement were recorded at 1 minute intervals. The data collected this way was used to calculate CTE based on AASHTO TP60 procedure as well as the Texas DOT modified test procedure. A typical graph showing the Texas DOT method is shown in Figure 3-11.

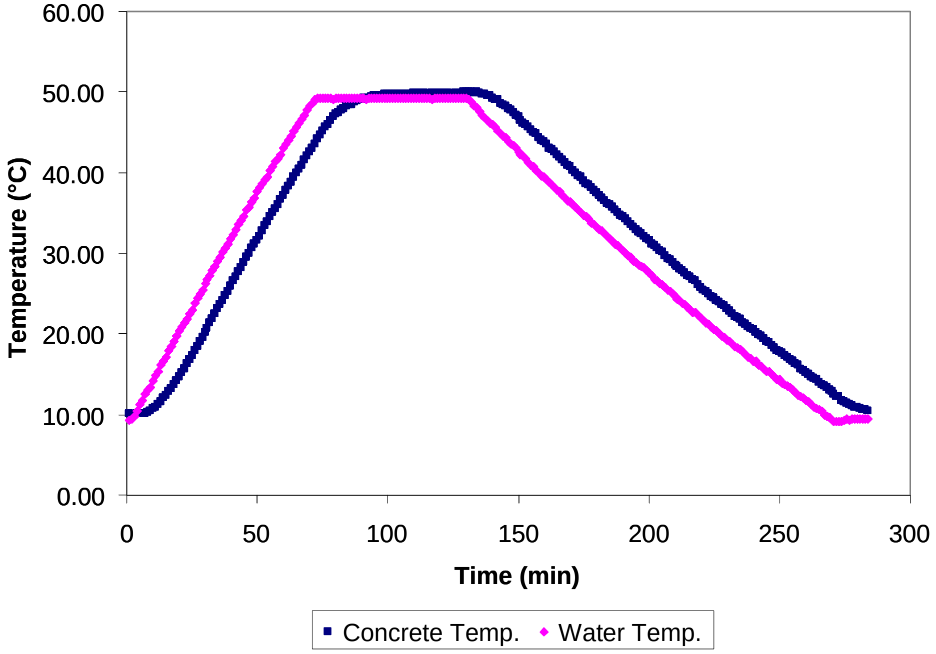


Figure 3-10. A Typical Concrete and Water Temperature Graph

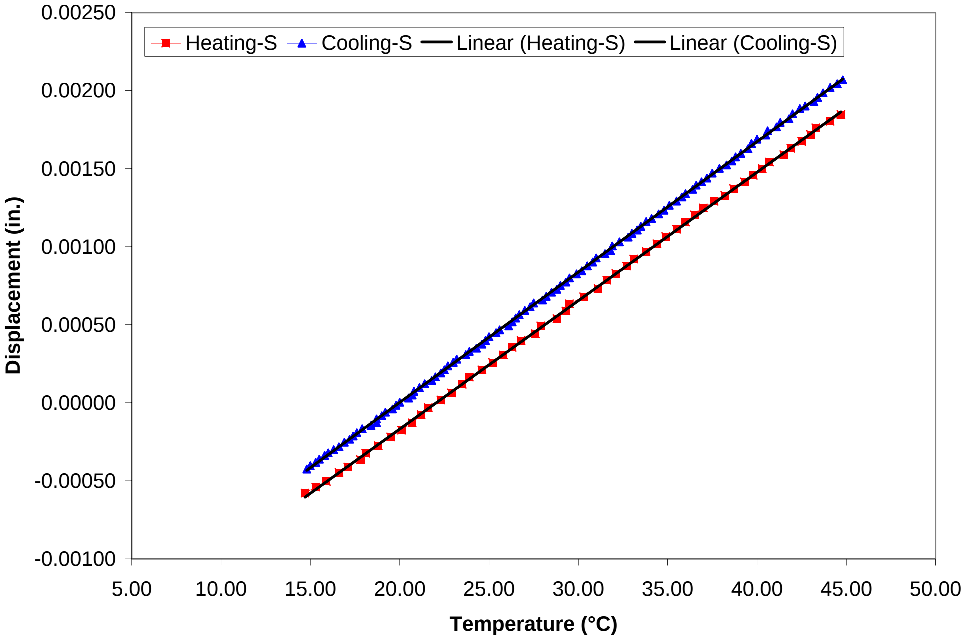


Figure 3-11. A Typical Texas DOT Method Graph

3.3.6 CTE Calculations

Based on the sample temperature and displacements the following computational sequence is followed to establish CTE value.

The CTE test result is the average of heating and cooling cycle CTE values providing that the difference between the values does not exceed 0.5 με/°F (0.3 με/°C).

$$CTE = (CTE_{HEATING} + CTE_{COOLING}) / 2$$

CTE of the heating or cooling cycle is defined as the actual length change of the specimen (ΔL_{ACTUAL}) divided by the initial length of the specimen ($L_{INITIAL}$) over the temperature range (ΔT).

$$CTE_{\text{HEATING or COOLING}} = (\Delta L_{ACTUAL} / L_{INITIAL}) / \Delta T$$

The actual length change is defined as the summation of the measured length change of the specimen ($\Delta L_{SPECIMEN}$) and the length change of the measuring apparatus ($\Delta L_{APPARATUS}$).

$$\Delta L_{ACTUAL} = \Delta L_{SPECIMEN} + \Delta L_{APPARATUS}$$

The length change of the measuring apparatus is the product of the correction factor of the measuring apparatus (C_f), initial length of the specimen ($L_{INITIAL}$), and the temperature range (ΔT).

$$\Delta L_{APPARATUS} = C_f \times L_{INITIAL} \times \Delta T$$

The correction factor of the measuring apparatus is obtained according to Appendix X.2 of the AASHTO TP60 standard. *(18)*

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter documents the results of the laboratory experimental program described in Chapter 3. The results summarized in this chapter include (i) physical properties of aggregates; (ii) fresh and hardened properties of the concrete; and (iii) coefficient of thermal expansion of concrete made from various aggregate rock types. Furthermore, the statistical and operational significance of test variables on the magnitude of CTE are presented in this chapter. The structural design implications of CTE are also summarized as part of this chapter.

4.2 Physical Properties of Coarse Aggregates

The absorption capacity and specific gravity tests (ASTM C127) were conducted on sampled aggregates. For each aggregate type, the sample was divided into four batches and tests were conducted on each batch. The results were then averaged. The summarized results are presented in Table 4-1.

Table 4-1. Physical Properties of Coarse Aggregates

Mix ID	Primary Aggregate Class	Pit Number	Absorption Capacity, %	Specific Gravity		
				Apparent	Bulk Saturated Surface-Dry	Bulk Dry
CTE 1	Limestone	71-47	1.13	2.655	2.591	2.552
CTE 2	Gravel	19-56	2.77	2.762	2.637	2.566
CTE 3	Dolomitic Limestone	75-05	0.69	2.698	2.668	2.649
CTE 4	Slag	82-19	3.47	2.490	2.393	2.329
CTE 5	Dolomite	49-65	0.68	2.787	2.753	2.735
CTE 6	Gabbro (Trap Rock)	95-10	0.21	2.928	2.916	2.910
CTE 7	Dolomite	58-11	3.13	2.769	2.628	2.548

4.3 Fresh Concrete Properties

Fresh concrete properties results conducted according to aforementioned standards (Table 3.6) are shown in Table 4-2. The target slump was 3 ± 0.5 in. and the target air content was 6.5 ± 1.5 %. It should be mentioned that these tests were conducted to make sure that the concrete tested in laboratory is not significantly different from the concrete used in field for paving. However, strict conformance to field parameters was not the goal of this study.

Table 4-2. Fresh Concrete Properties

Mix ID	Test Parameter			
	Slump, inches	Air, %	Unit Weight, pcf	Temperature, °F
CTE 1	3.0	6.0	147.0	54
CTE 2	4.0	5.2	149.4	70
CTE 3	6.0	6.0	145.0	70
CTE 4	3.0	5.8	145.4	77
CTE 5	3.8	4.2	150.8	75
CTE 6	4.0	5.0	152.0	61
CTE 7	3.0	4.9	148.2	69

4.4 Hardened Concrete Properties

Hardened concrete properties tests were conducted on laboratory cured specimens at 1, 3, 7, 14, 28, 90, and 365 days after casting. Results are summarized in Figures 4-1 through 4-31. The data used for developing the summary tables and graphs are presented in Appendix B. Dashed lines in the plots represent the target 28-day compressive and flexural strength as suggested by MDOT. Three replicate specimens were tested at each specified age. The error bars represent the standard deviation of test values among three replicates.

All concrete batches conformed to 28-day compressive strength of 3500 psi. Except for mix IDs 2 and 3, the flexural strength requirement of 720 psi was met. However, both of these mixes met the requirement at 90 days of age. The impact of this minor non-conformance on CTE is not going to be significant in the author’s opinion. The hardened concrete property tests were conducted for two reasons:

- To evaluate the quality of the concrete
- To be used as level 1 inputs in M-E PDG and HIPERPAV II software

In general, the delivered concrete met the required specified strengths. Table 4-3 presents the average 28-day hardened concrete properties.

Table 4-3. Average 28-Day Strength Properties (psi)

Mix ID	Test Parameter			
	Compressive Strength	Split Tensile Strength	Flexural Strength	Elastic Modulus ($*10^{-6}$)
CTE 1	5129	516	836	4.50
CTE 2	4965	502	692	4.89
CTE 3	3967	489	645	4.57
CTE 4	5169	507	831	4.66
CTE 5	4035	511	731	4.65
CTE 6	5125	500	731	5.39
CTE 7	5825	561	820	4.48
CTE 8	4953	489	N/A	4.71

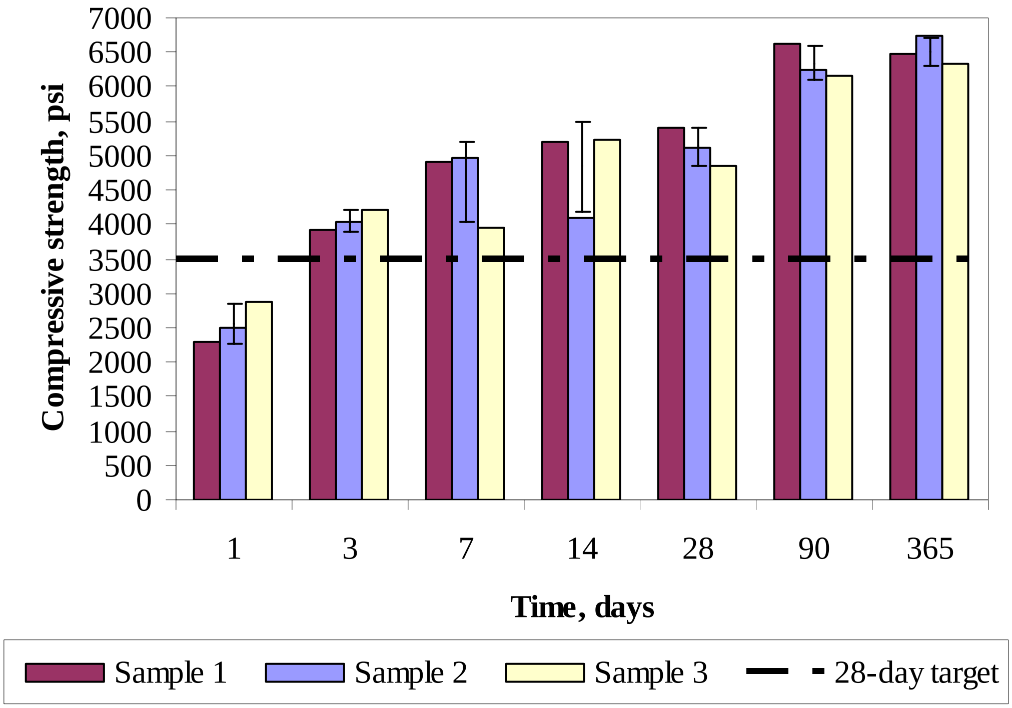


Figure 4-1. CTE 1 Compressive Strength

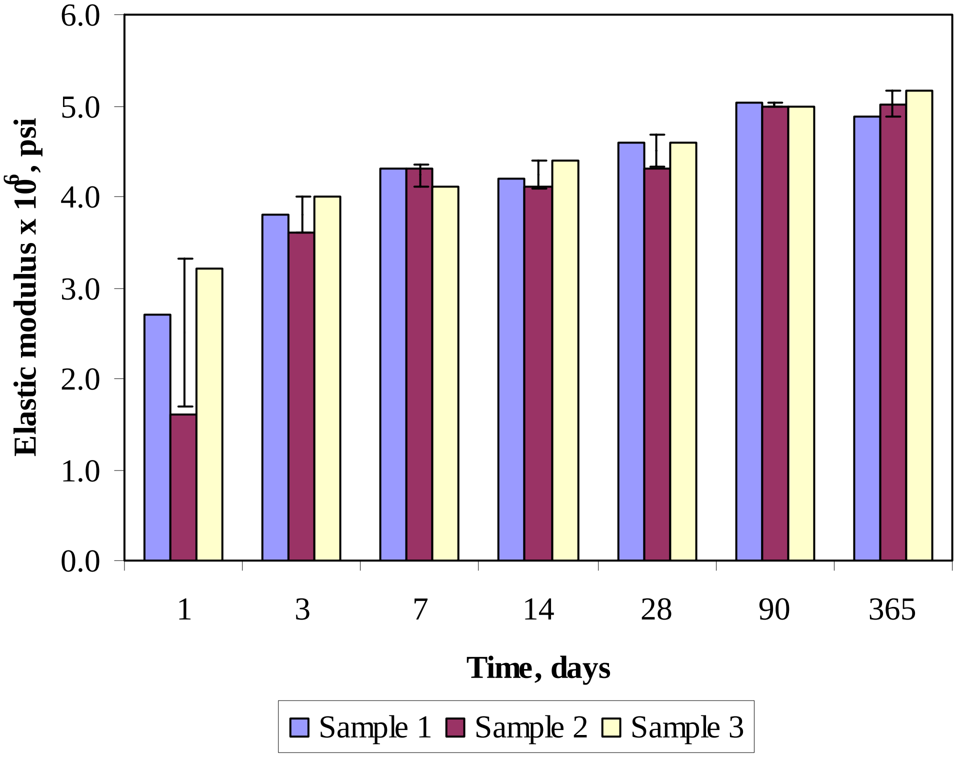


Figure 4-2. CTE 1 Elastic Modulus

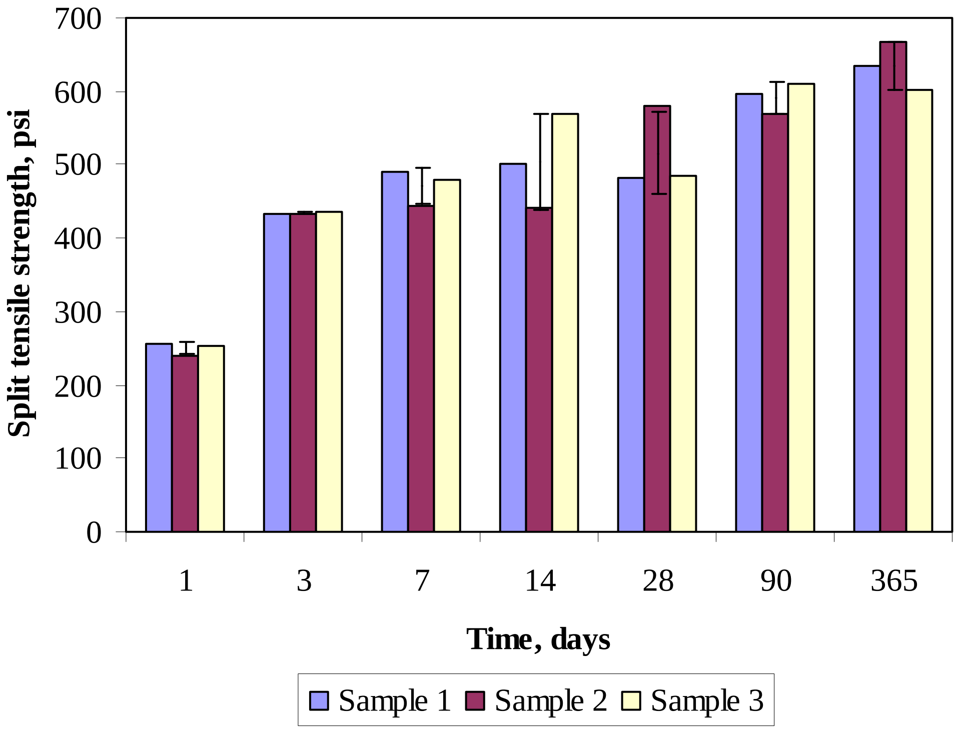


Figure 4-3. CTE 1 Splitting Tensile Strength

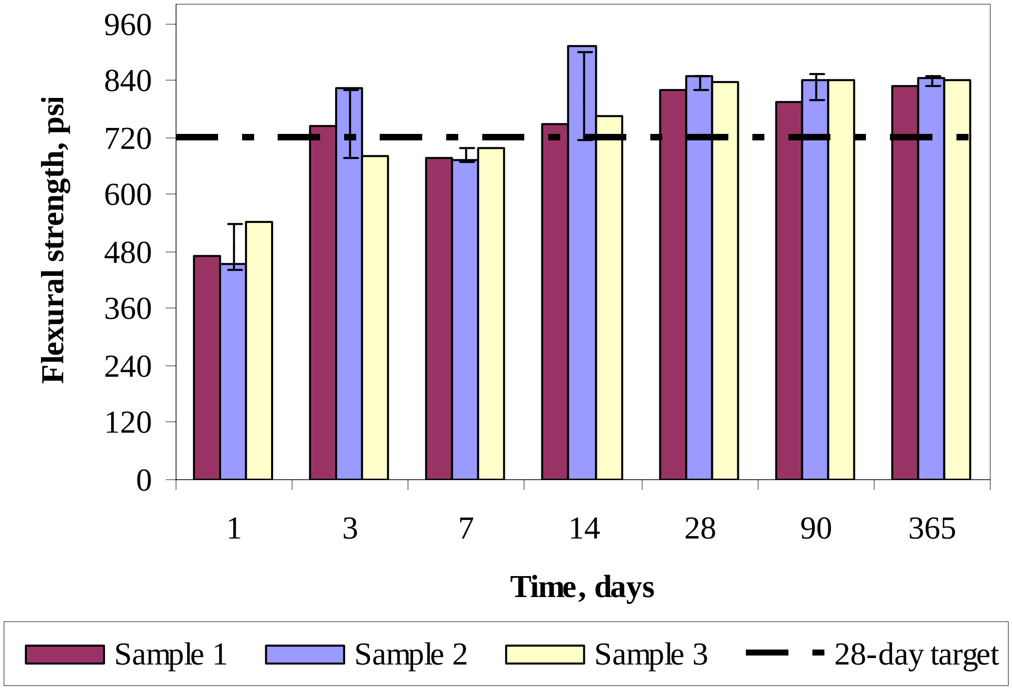


Figure 4-4. CTE 1 Flexural Strength

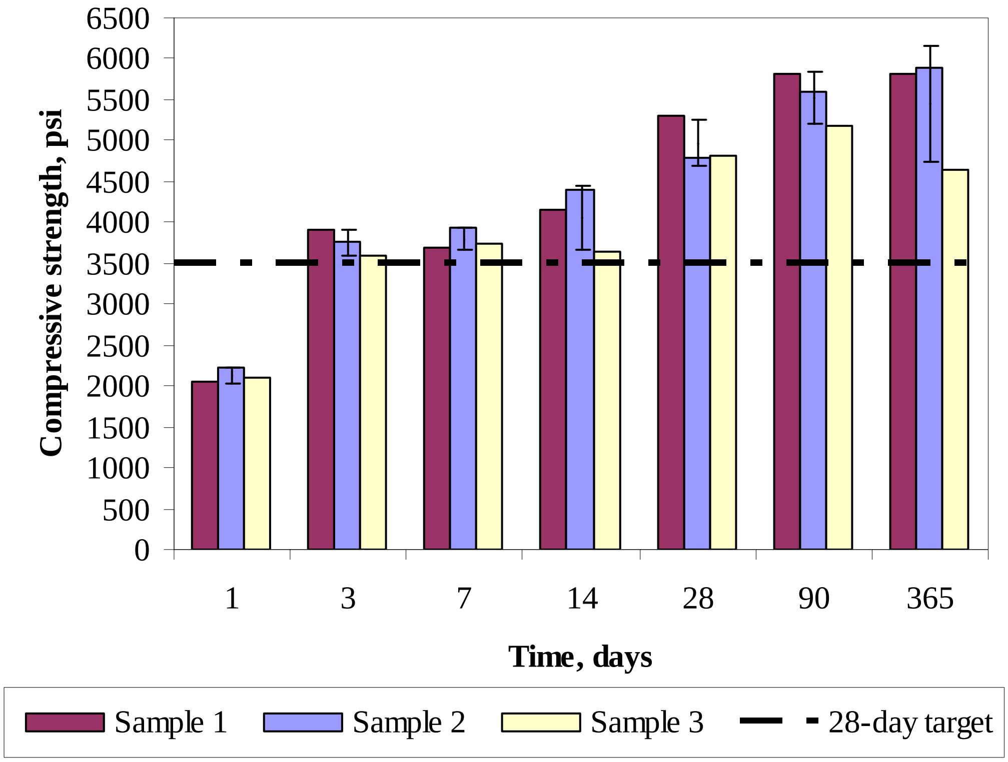


Figure 4-5. CTE 2 Compressive Strength

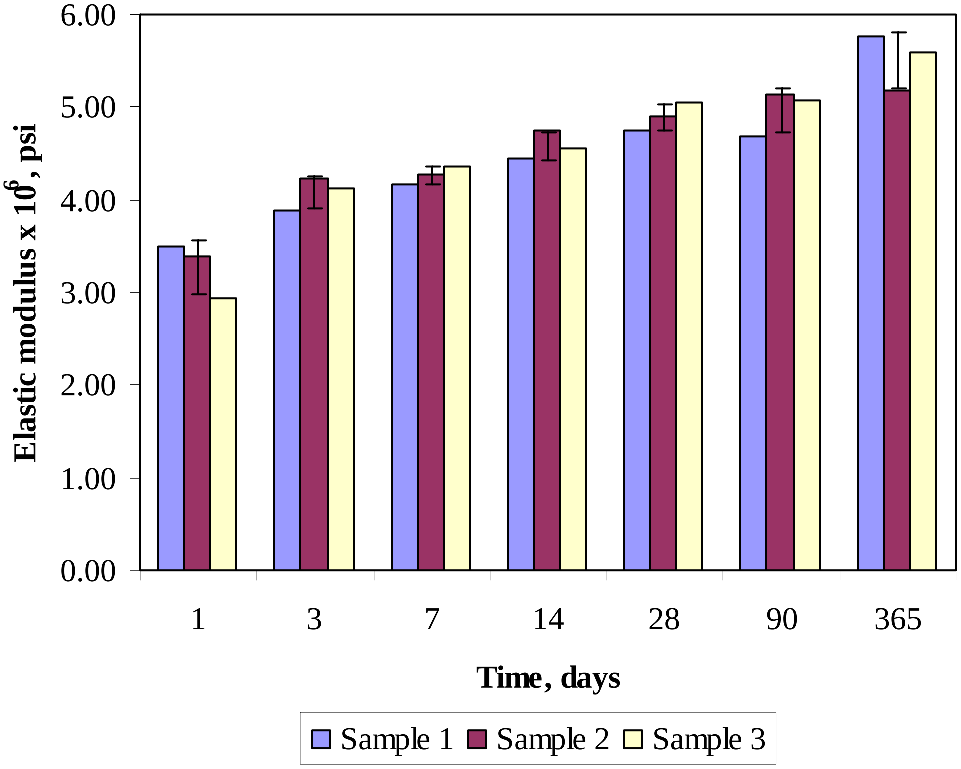


Figure 4-6. CTE 2 Elastic Modulus

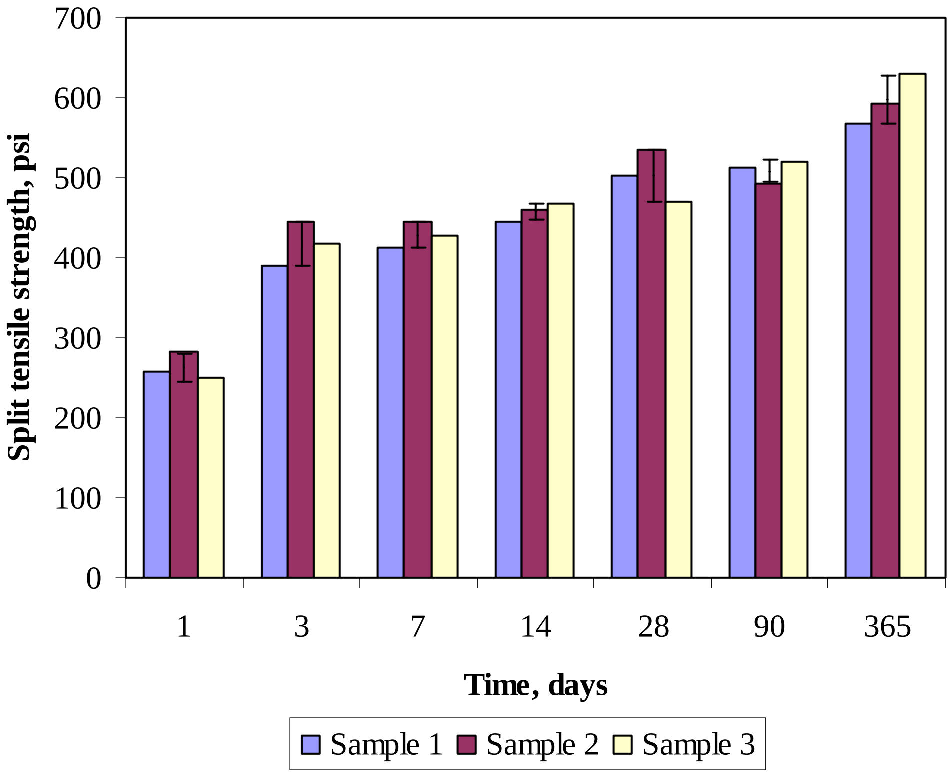


Figure 4-7. CTE 2 Splitting Tensile Strength

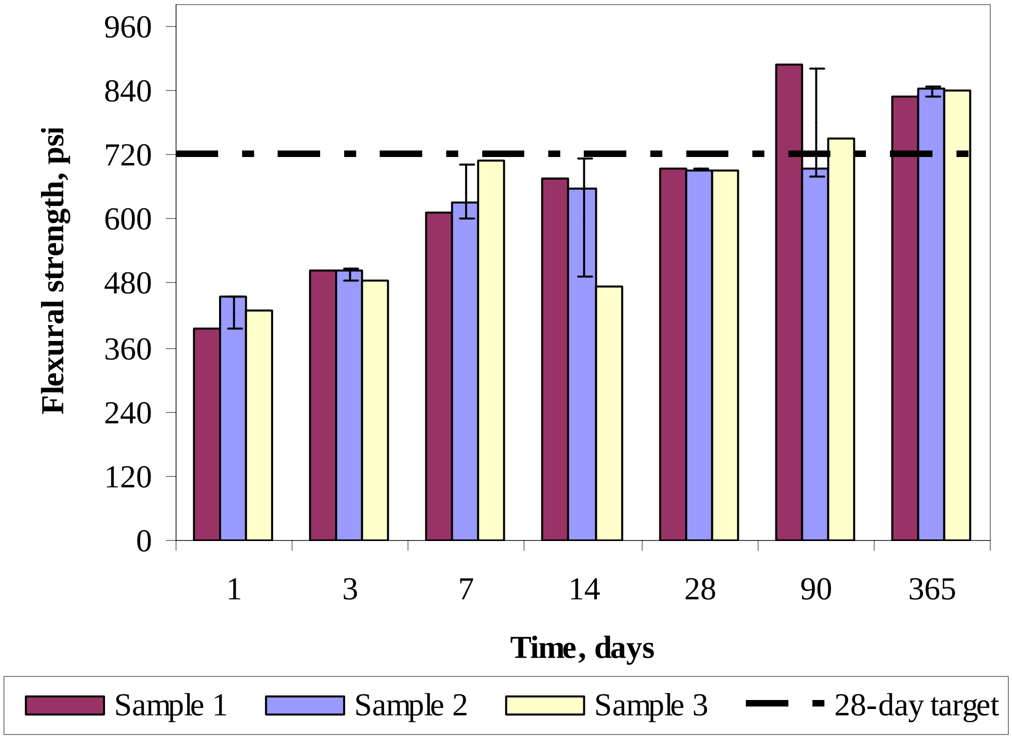


Figure 4-8. CTE 2 Flexural Strength

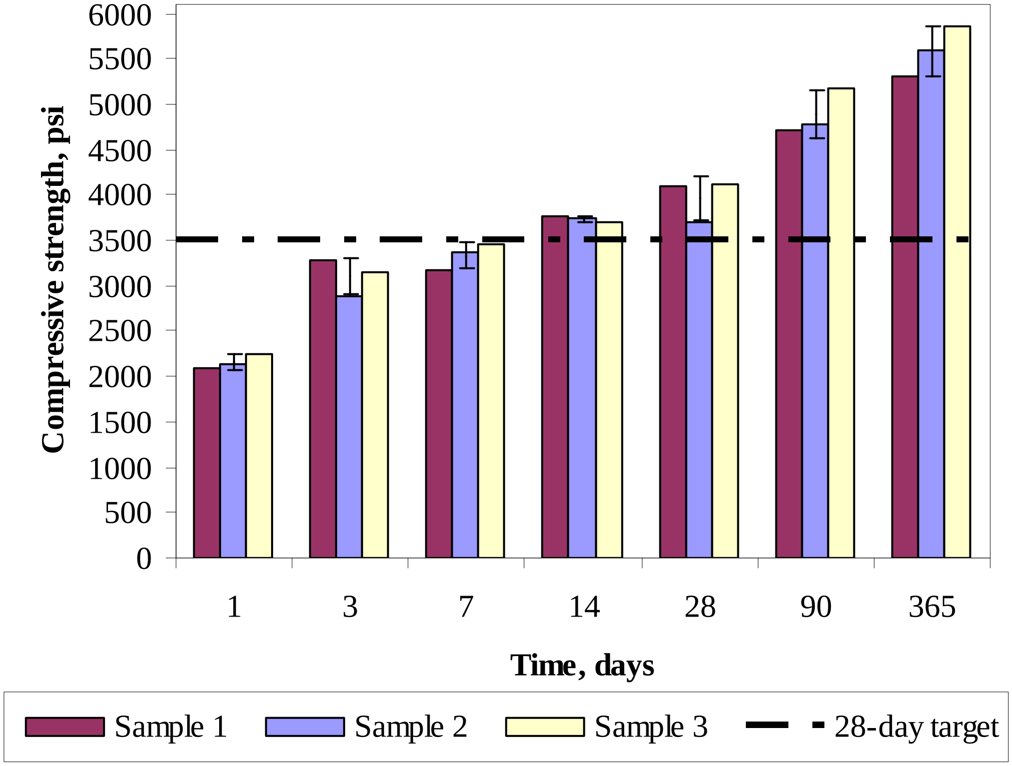


Figure 4-9. CTE 3 Compressive Strength

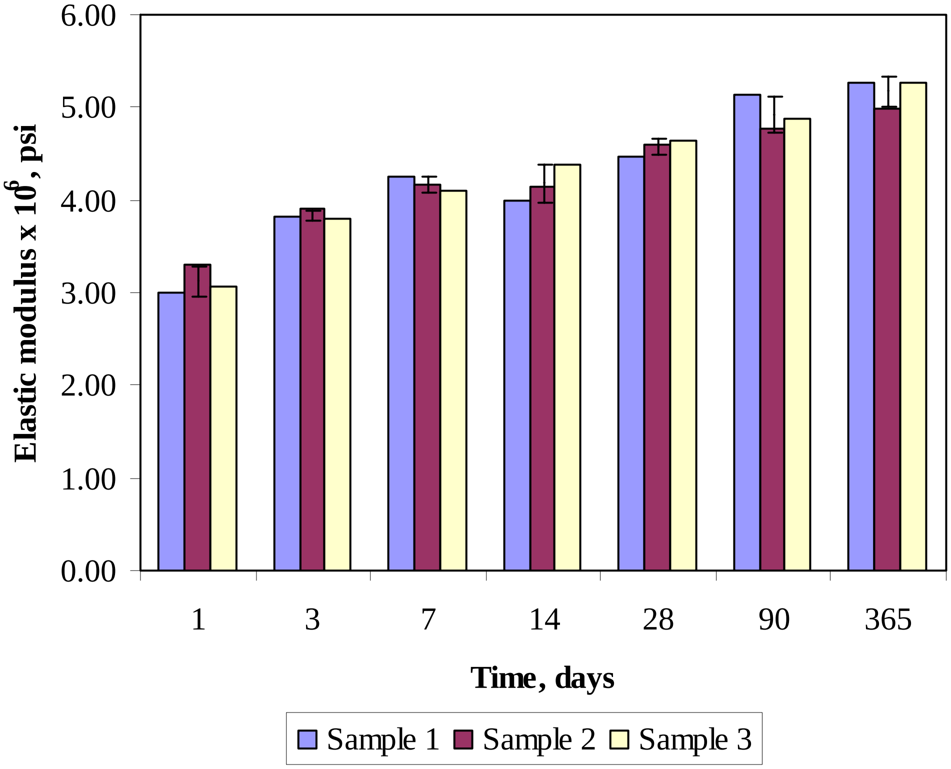


Figure 4-10. CTE 3 Elastic Modulus

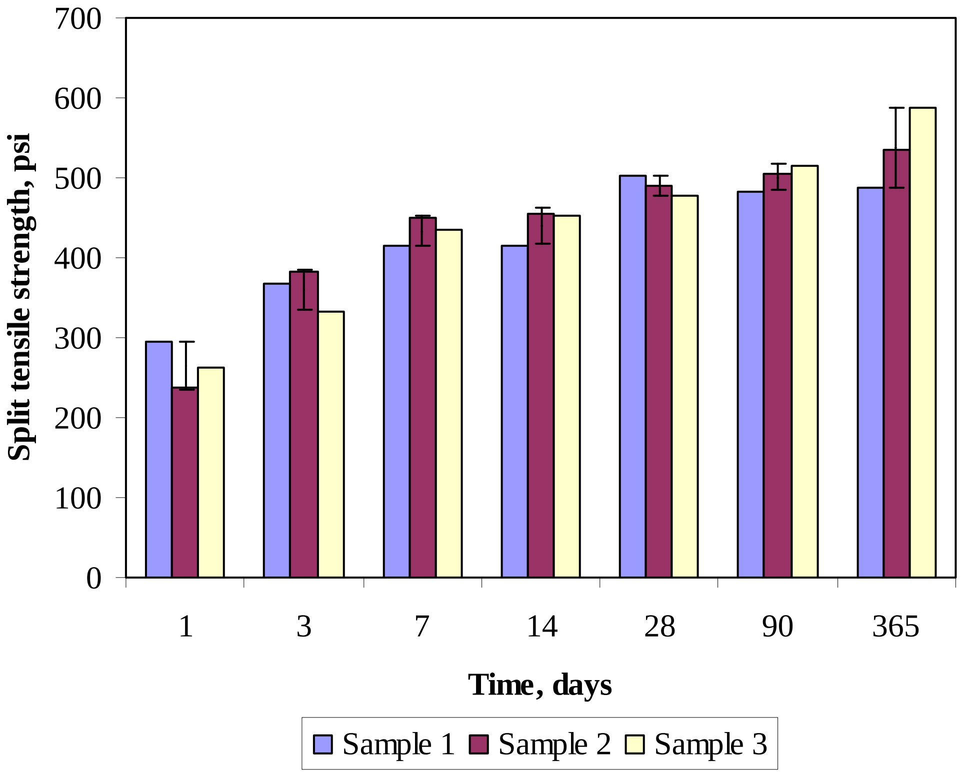


Figure 4-11. CTE 3 Splitting Tensile Strength

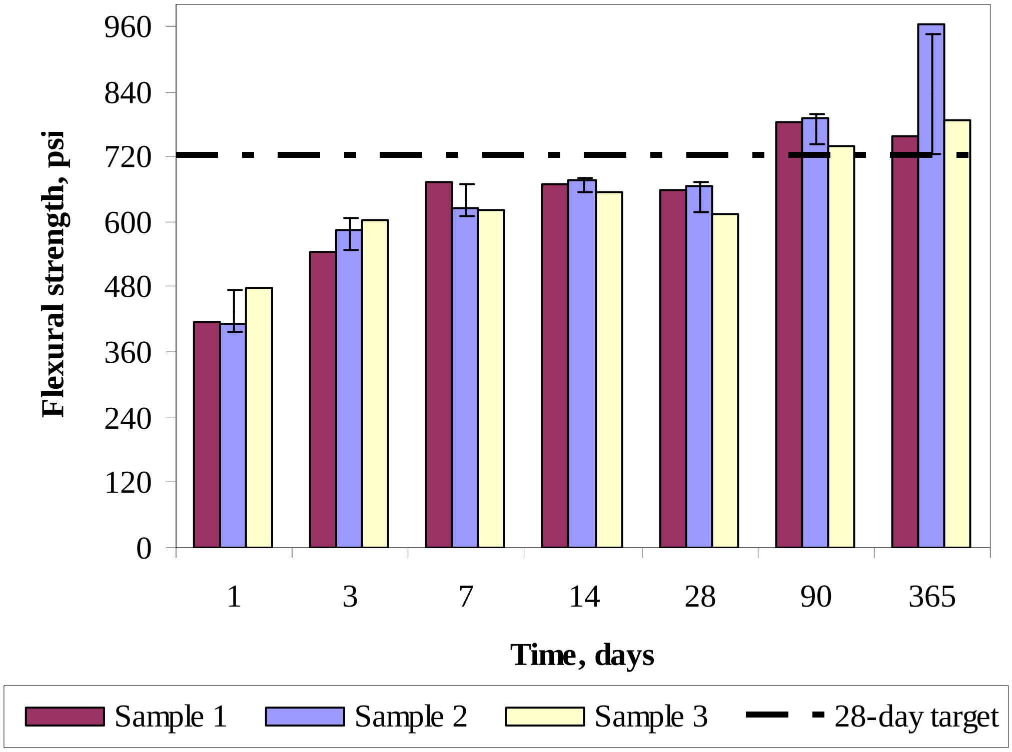


Figure 4-12. CTE 3 Flexural Strength

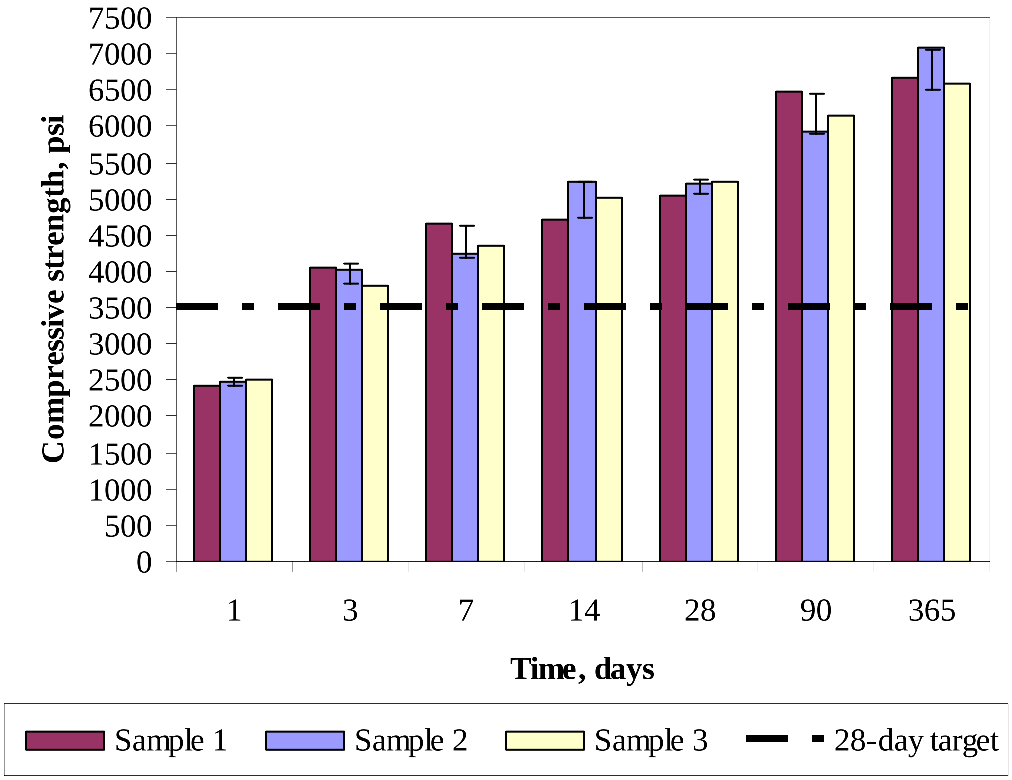


Figure 4-13. CTE 4 Compressive Strength

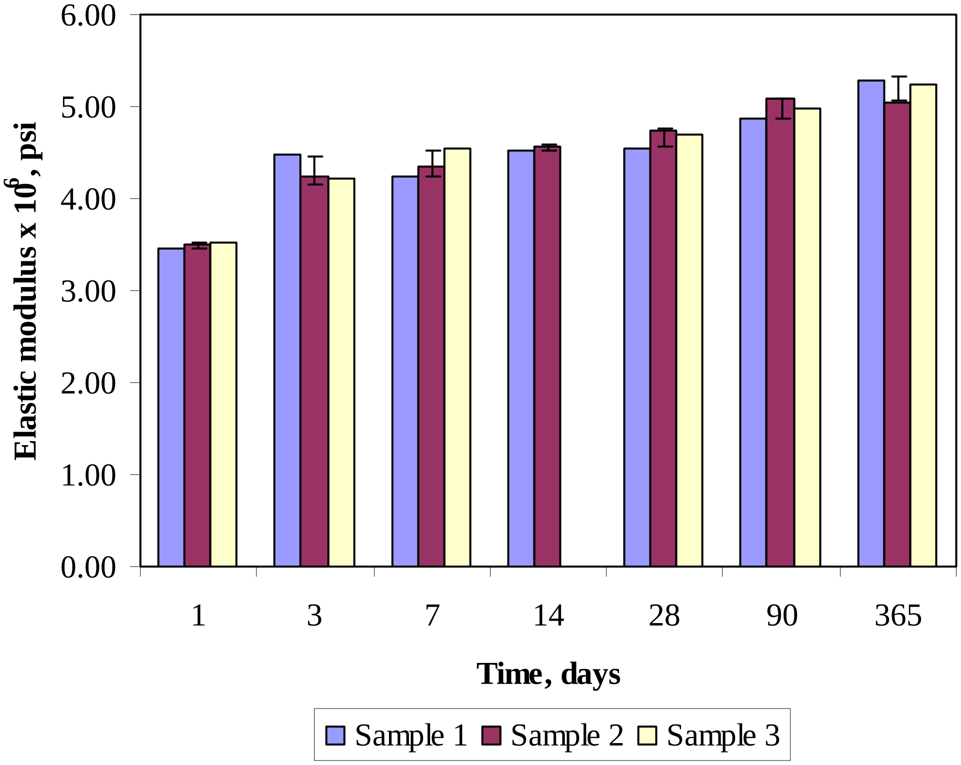


Figure 4-14. CTE 4 Elastic Modulus

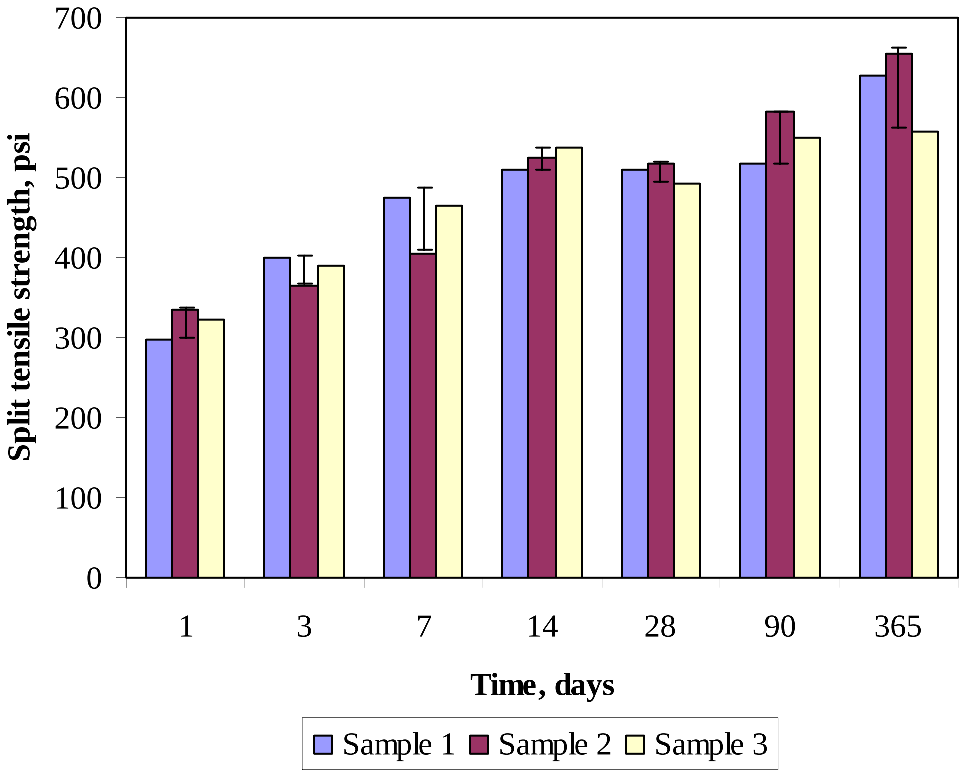


Figure 4-15. CTE 4 Splitting Tensile Strength

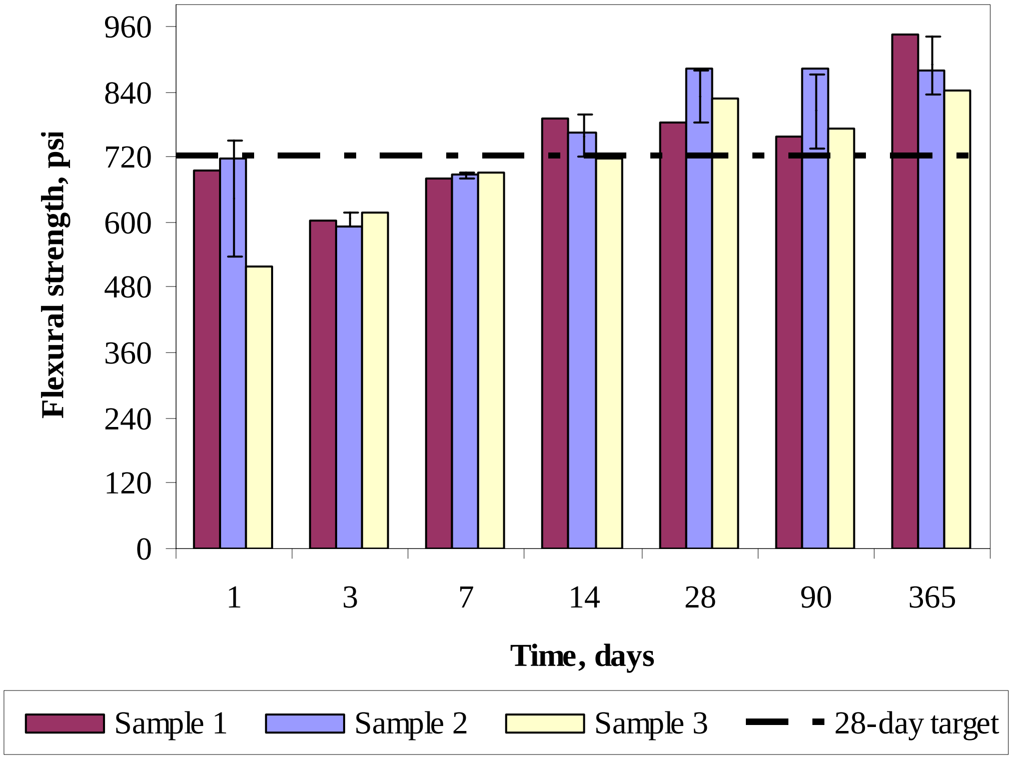


Figure 4-16. CTE 4 Flexural Strength

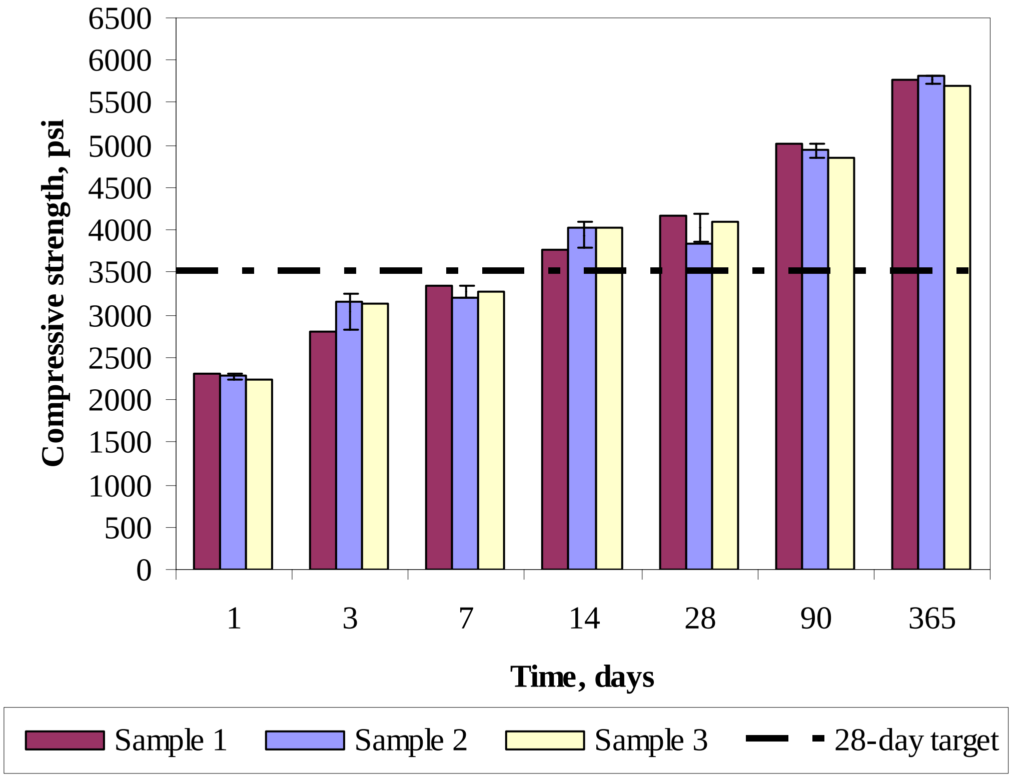


Figure 4-17. CTE 5 Compressive Strength

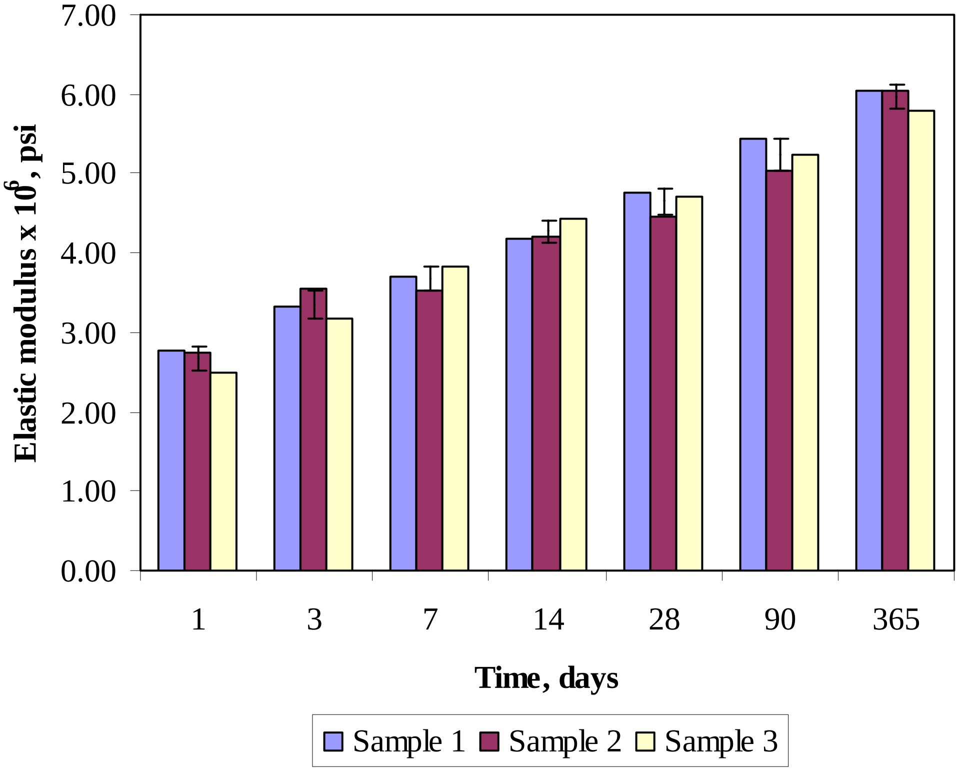


Figure 4-18. CTE 5 Elastic Modulus

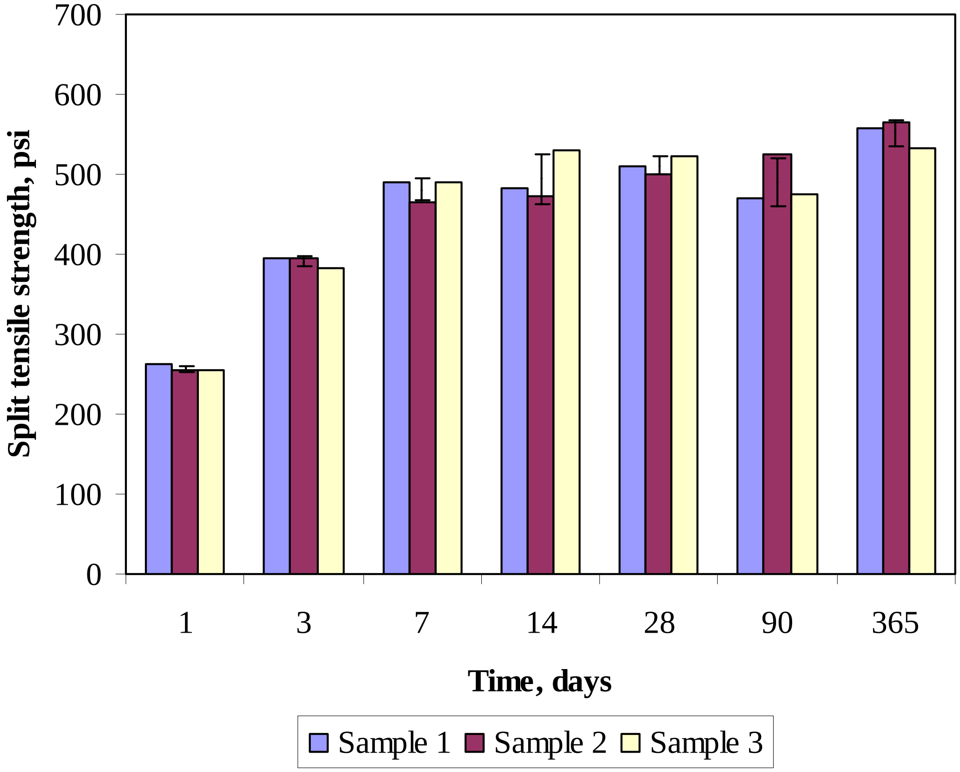


Figure 4-19. CTE 5 Splitting Tensile Strength

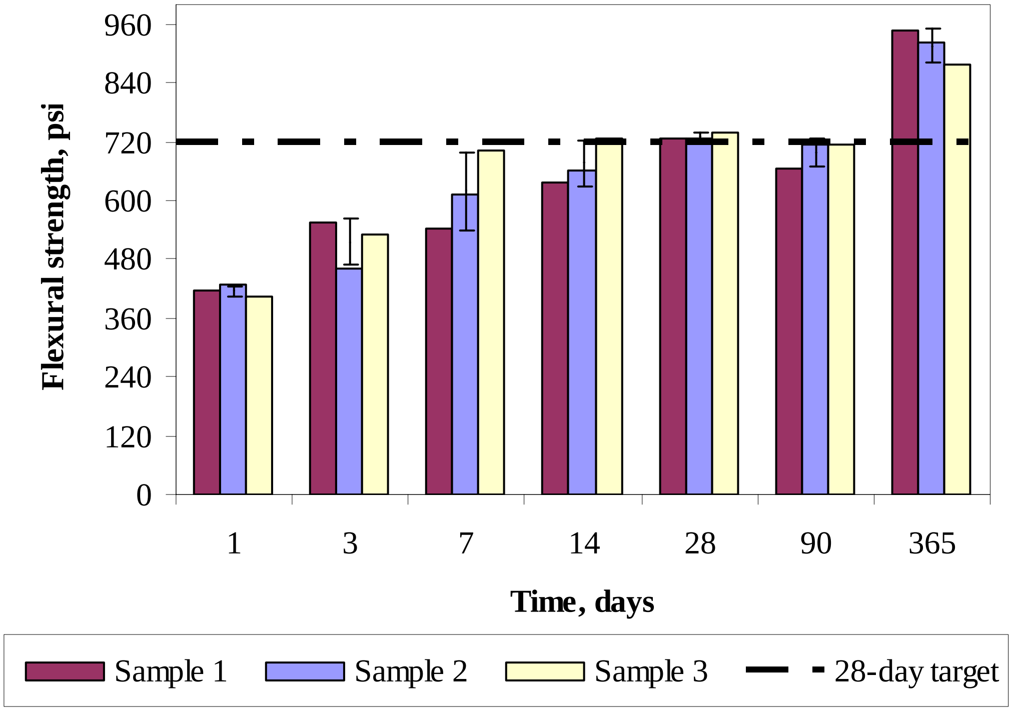


Figure 4-20. CTE 5 Flexural Strength

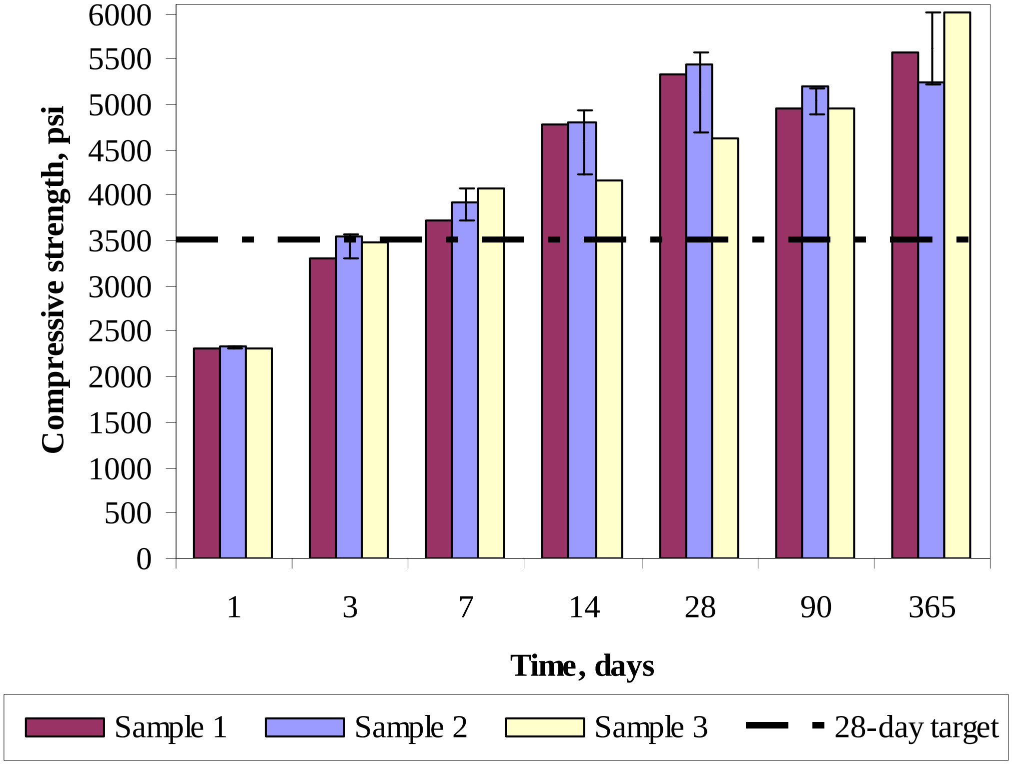


Figure 4-21. CTE 6 Compressive Strength

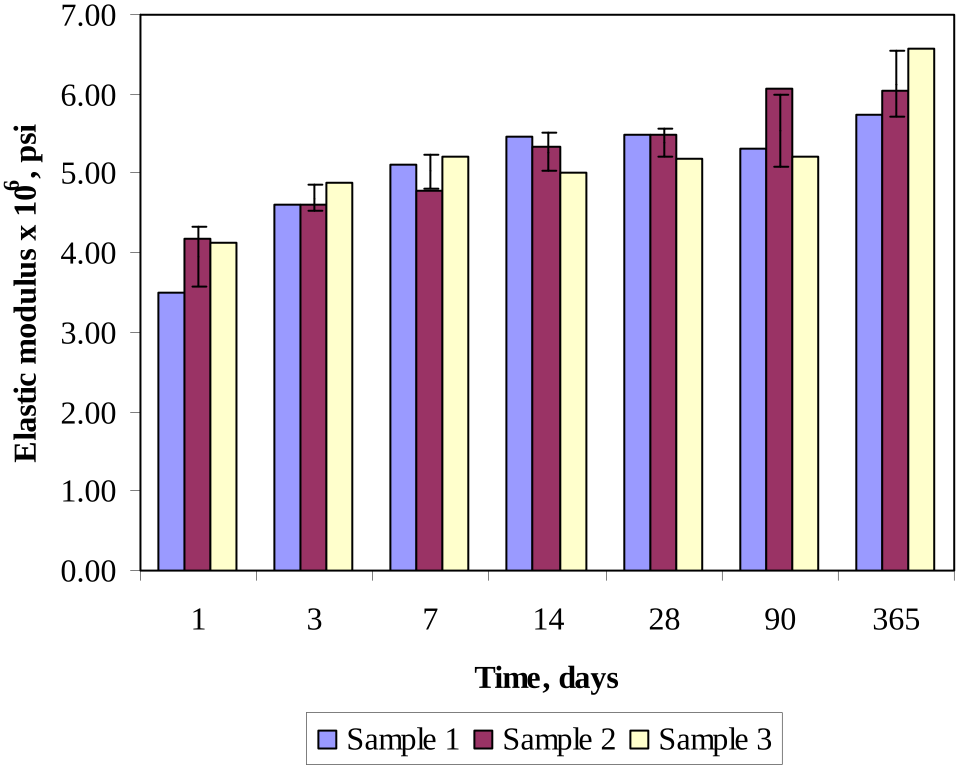


Figure 4-22. CTE 6 Elastic Modulus

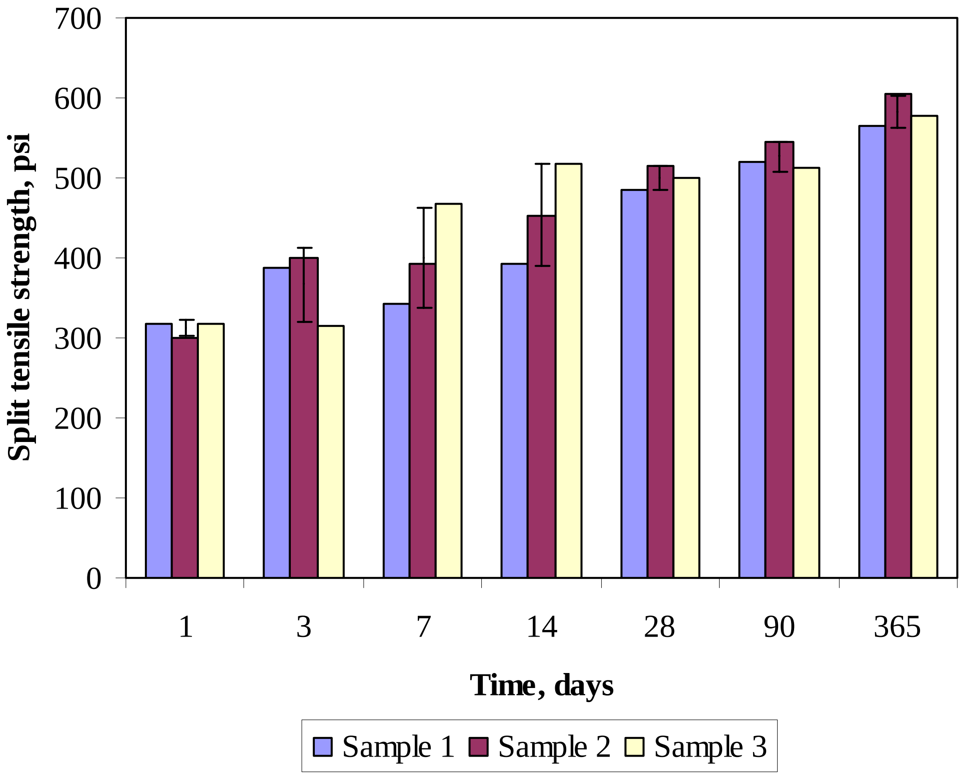


Figure 4-23. CTE 6 Splitting Tensile Strength

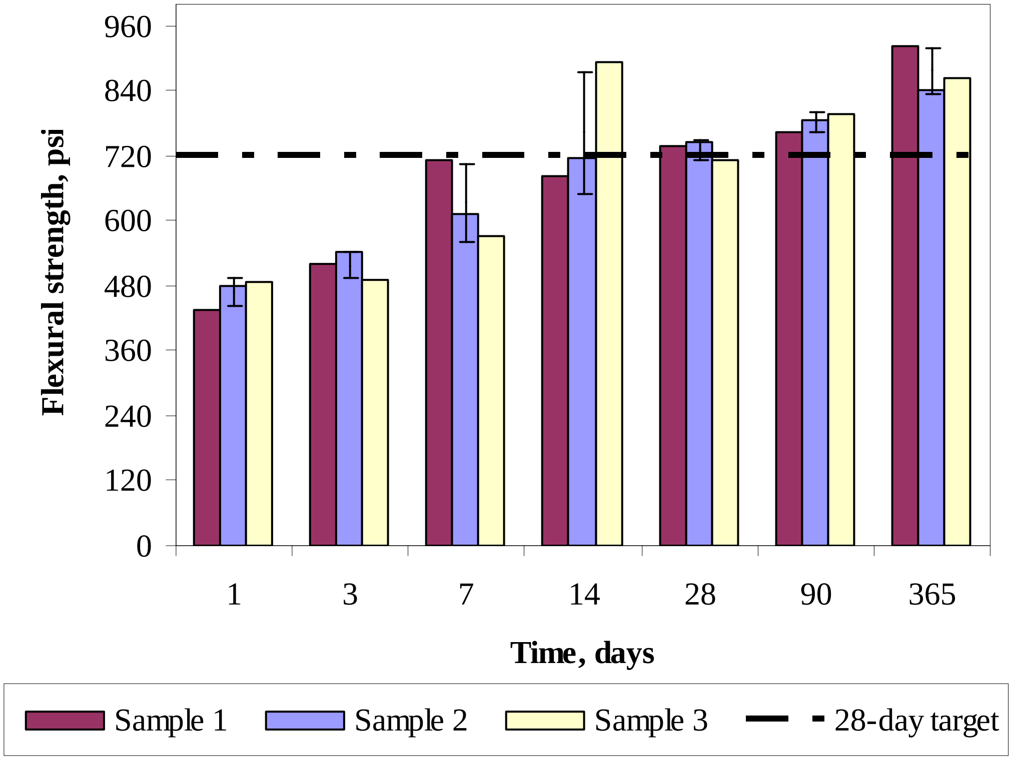


Figure 4-24. CTE 6 Flexural Strength

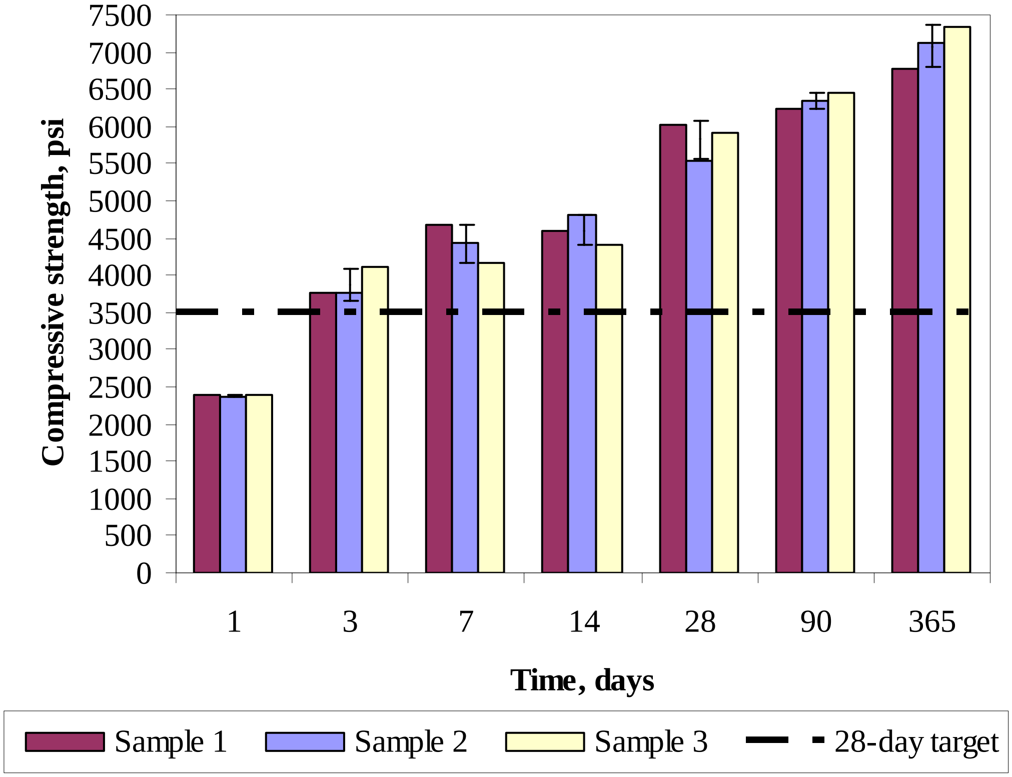


Figure 4-25. CTE 7 Compressive Strength

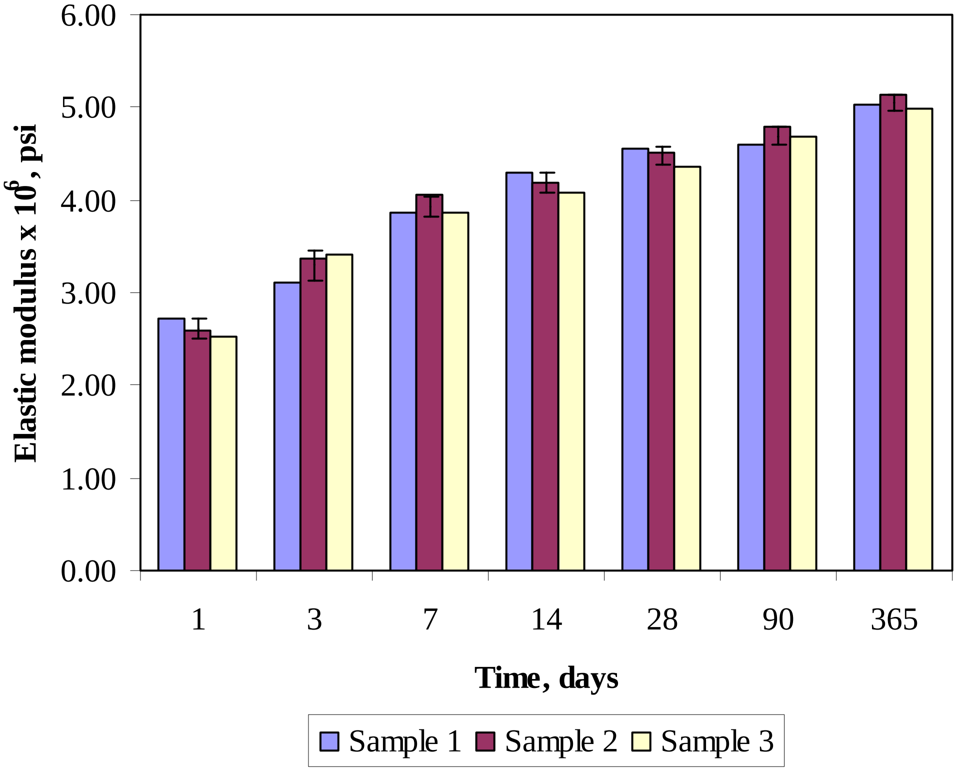


Figure 4-26. CTE 7 Elastic Modulus

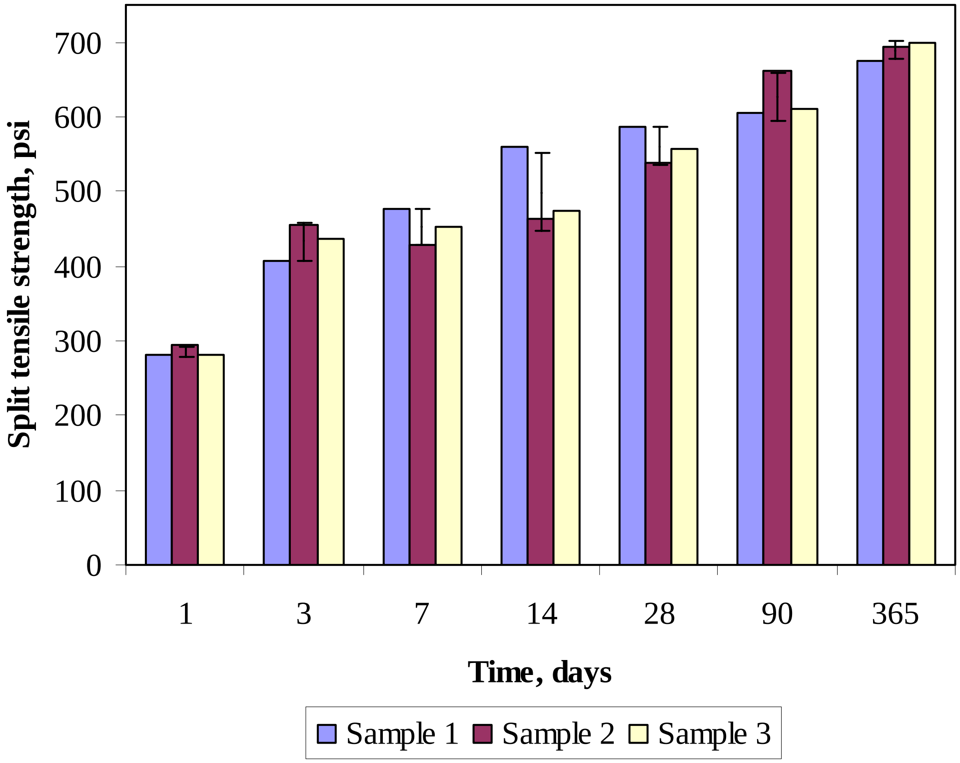


Figure 4-27. CTE 7 Splitting Tensile Strength

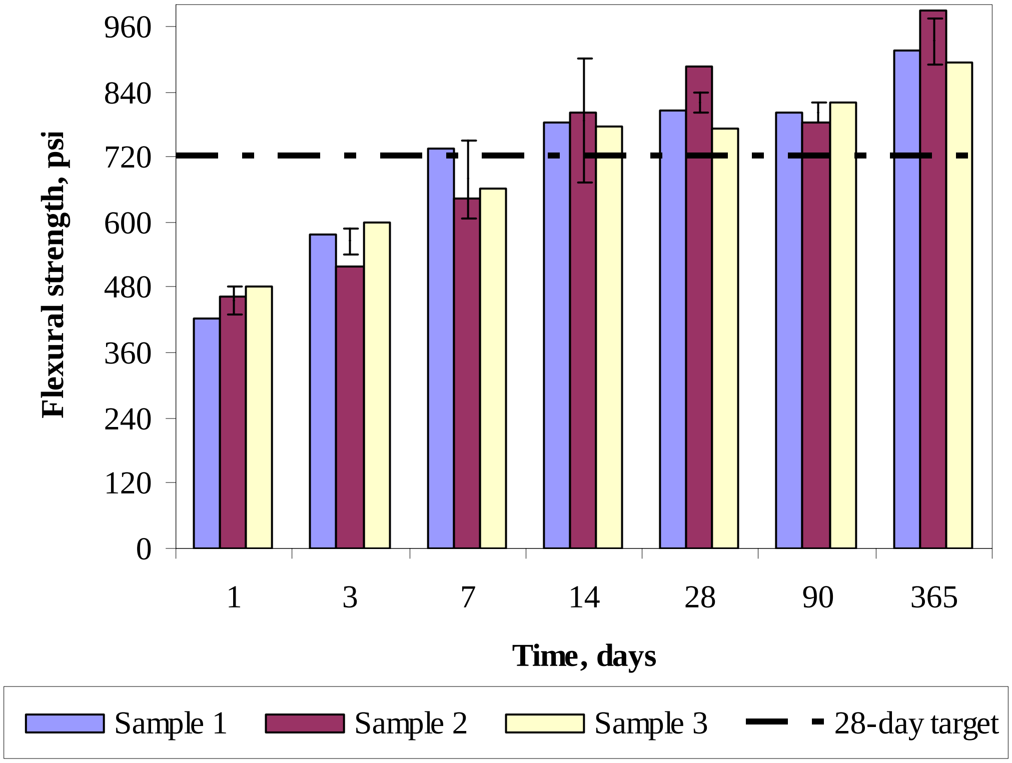


Figure 4-28. CTE 7 Flexural Strength

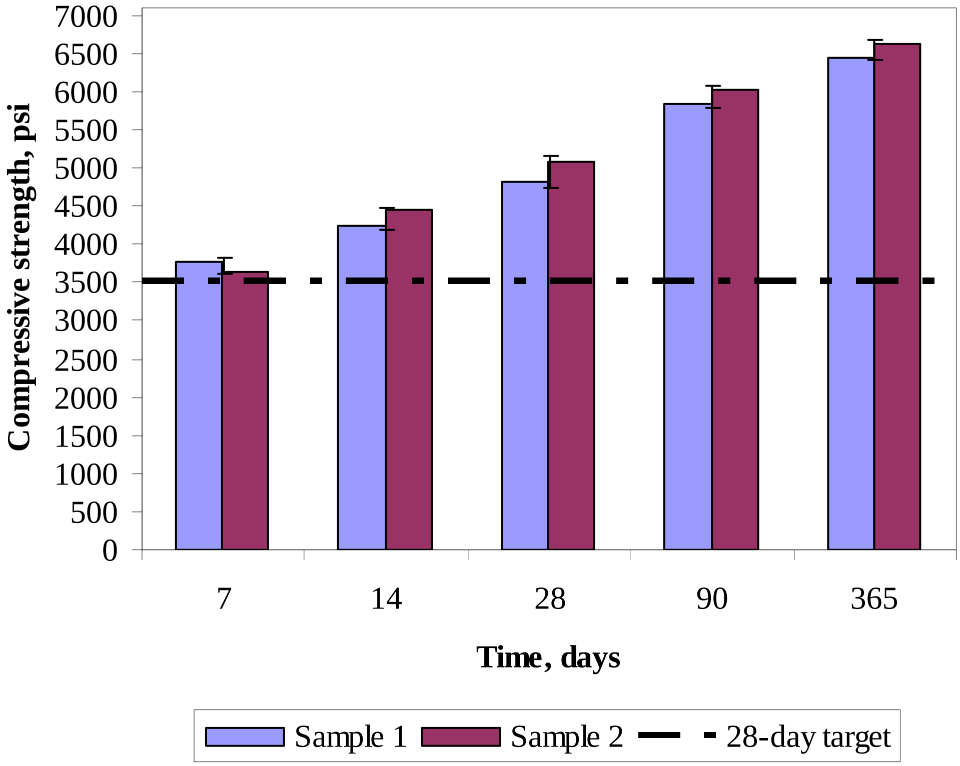


Figure 4-29. CTE 8 Compressive Strength*

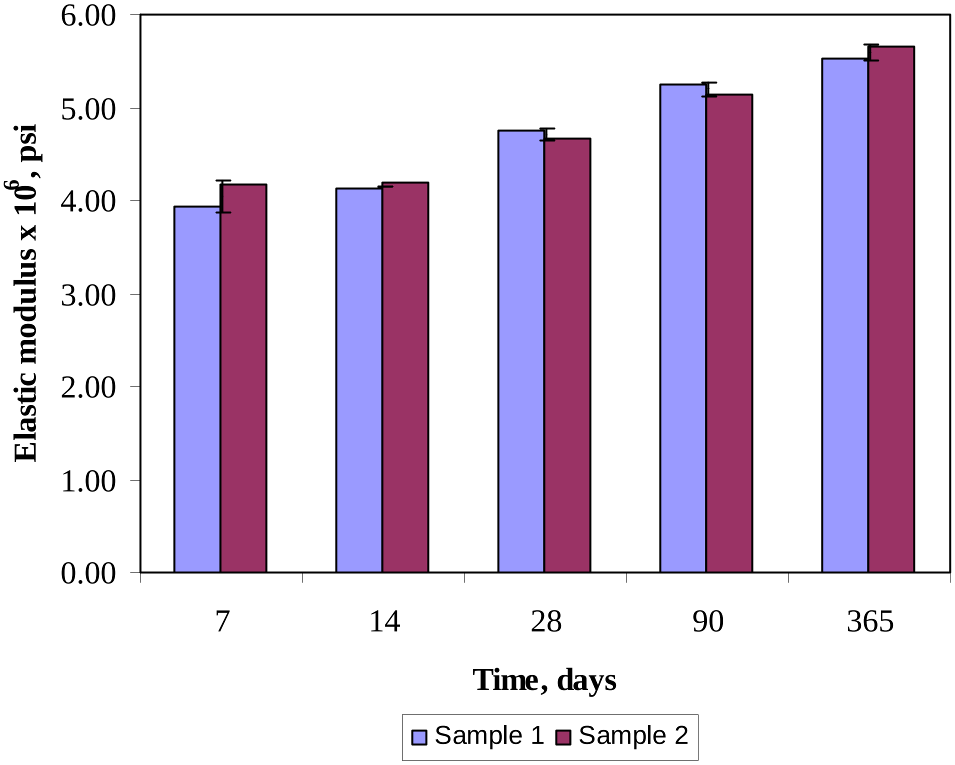


Figure 4-30. CTE 8 Elastic Modulus*

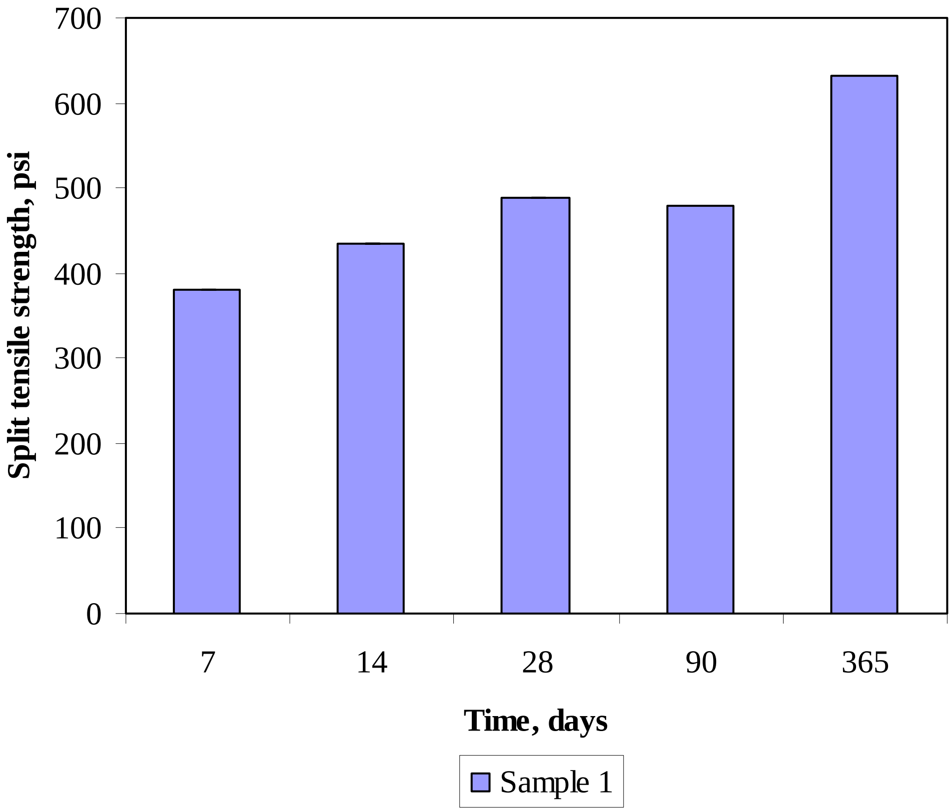


Figure 4-31. CTE 8 Splitting Tensile Strength*

** For CTE 8, there were a total of three specimens for each test age. After CTE test was conducted, two of the specimens were used for compressive strength and elastic modulus test, and the other specimen was used for splitting tensile test.*

4.5 Thermal Properties

The CTE test was conducted on laboratory cured specimens at 3, 7, 14, 28, 90, 180, and 365 days after casting. CTE was calculated based on both AASHTO TP60 and Texas DOT 428 A methods. The results are presented in Figures 4-32 through 4-39. The data used for computing the summary information are presented in Appendix C. The error bars in these figures show the standard deviation of the test specimens based on three replicates. The dashed lines show the typical CTE ranges for concretes made with that particular aggregate based on "Guide for Mechanistic-Empirical Design" 1-37A *(19)* which are shown in Table 4-4.

The average 28 day CTE values of concrete samples made with limestone (CTE 1,3) were 4.54 and 4.51 με/°F (8.18 and 8.11 με/°C). For concrete made with dolomite coarse aggregate (CTE 5, 7, and 8) the average 28 day values ranged from 5.87 to 5.92 με/°F (10.57 to 10.65 με/°C). For concrete samples made with gravel aggregate (CTE 2), this value was 5.84 με/°F (10.52 με/°C). The value for concrete made with slag (CTE 4) was 5.71 με/°F (10.27 με/°C). The average 28 day CTE value obtained for concrete made with gabbro (trap rock) was 5.41 με/°F (9.73 με/°C).

Table 4-4. Typical CTE Ranges for Common Components and Concrete *(19)*

Material Type	Coefficient of Thermal Expansion, 10^{-6}/°F	Concrete Coefficient of Thermal Expansion (made from this material), 10^{-6}/°F
Aggregates		
Marbles	2.2-3.9	2.3
Limestones	2.0-3.6	3.4-5.1
Granites & Gneisses	3.2-5.3	3.8-5.3
Syenites, Diorites, Andesite, Basalt, Gabbros, Diabase	3.0-4.5	4.4-5.3
Dolomites	3.9-5.5	5.1-6.4*
Blast Furnace Slag		5.1-5.9
Sandstones	5.6-6.7	5.6-6.5
Quartz Sands & Gravels	5.5-7.1	6.0-8.7
Quartzite, Cherts	6.1-7.0	6.6-7.1
Cement Paste (saturated)		
w/c = 0.4 to 0.6	10-11	--
Concrete Cores		
Cores from LTPP pavement sections, many of which were used in calibration	N/A	$4.0*10^{-6}$– $5.5*10^{-6}$– $7.2*10^{-6}$ (Min – Mean – Max)

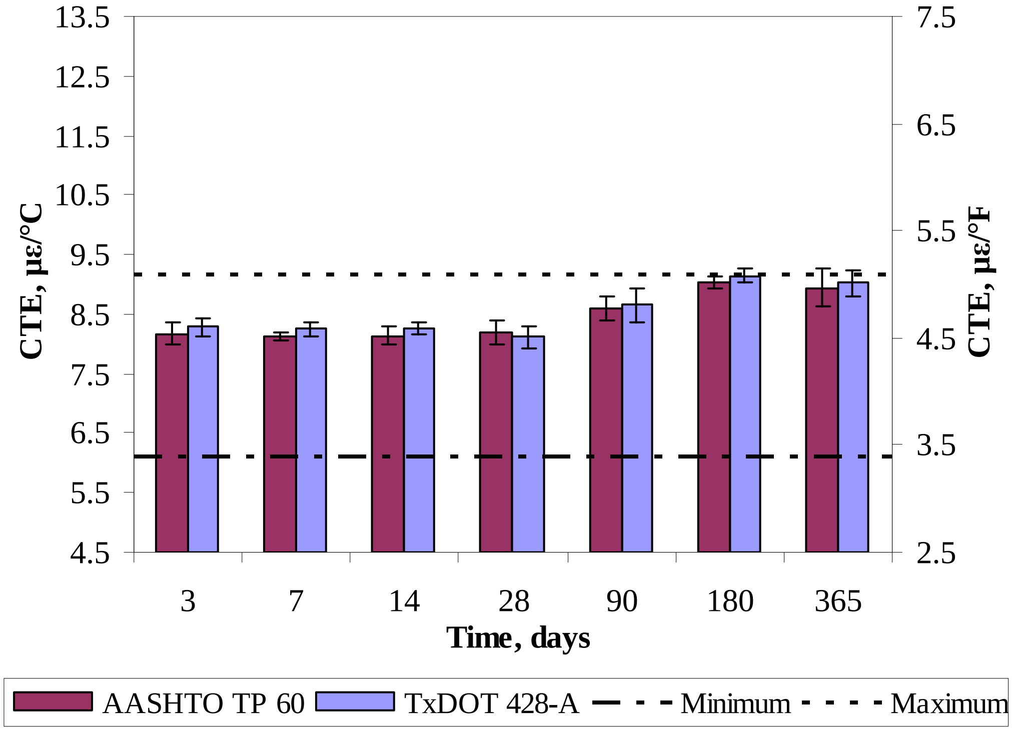


Figure 4-32. CTE 1 (Limestone Concrete) Coefficient of Thermal Expansion

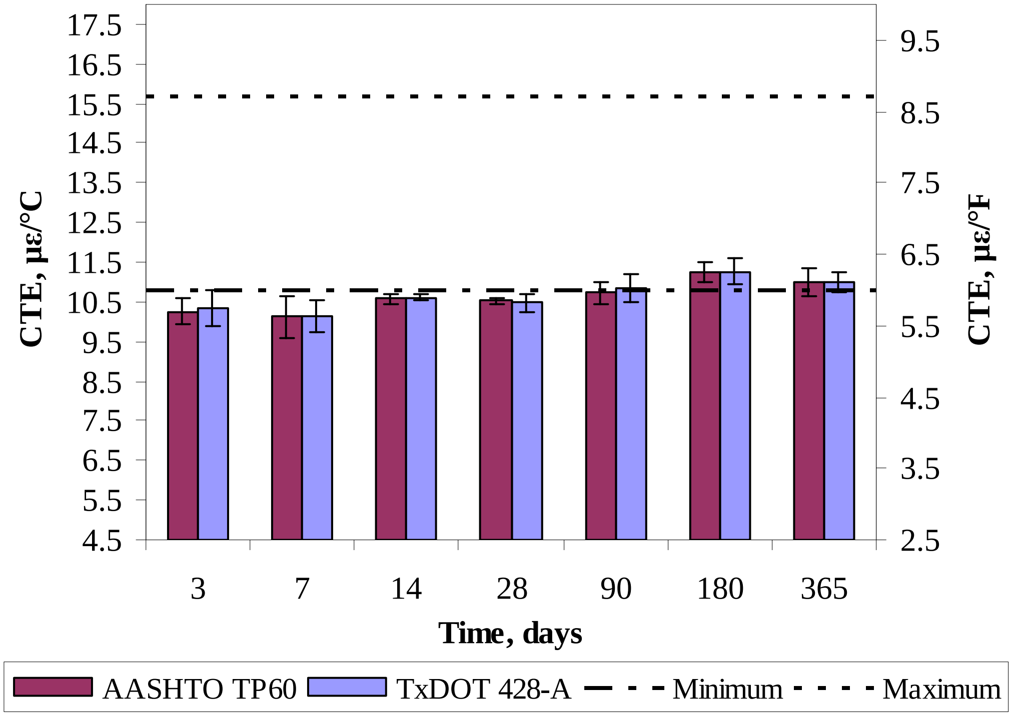


Figure 4-33. CTE 2 (Gravel Concrete) Coefficient of Thermal Expansion

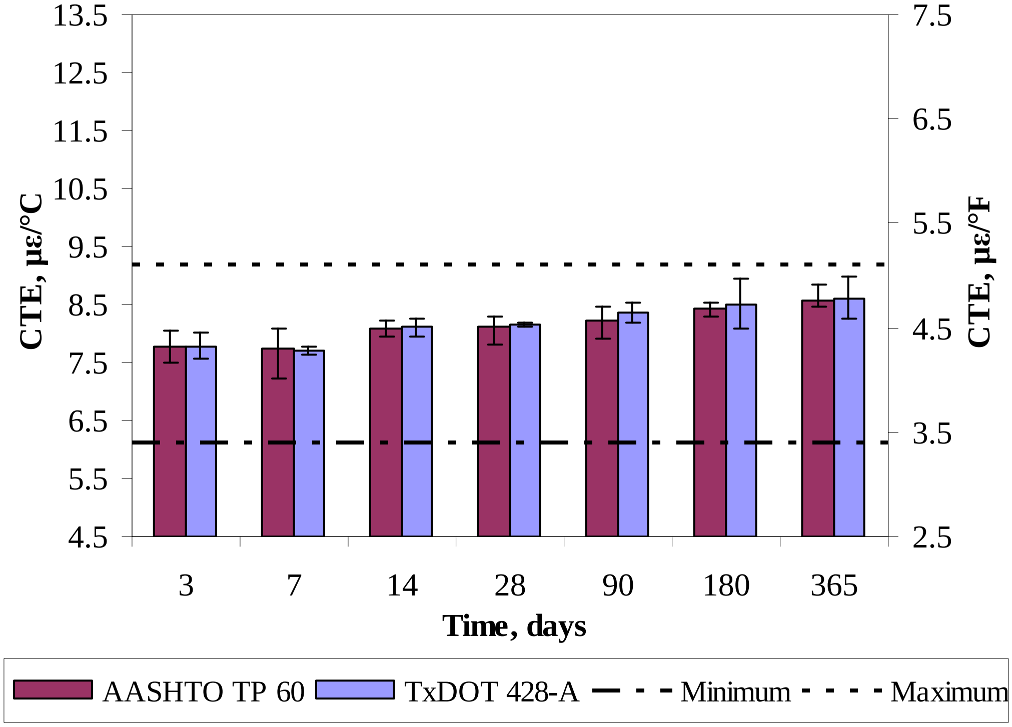


Figure 4-34. CTE 3 (Dolomitic Limestone Concrete) Coefficient of Thermal Expansion

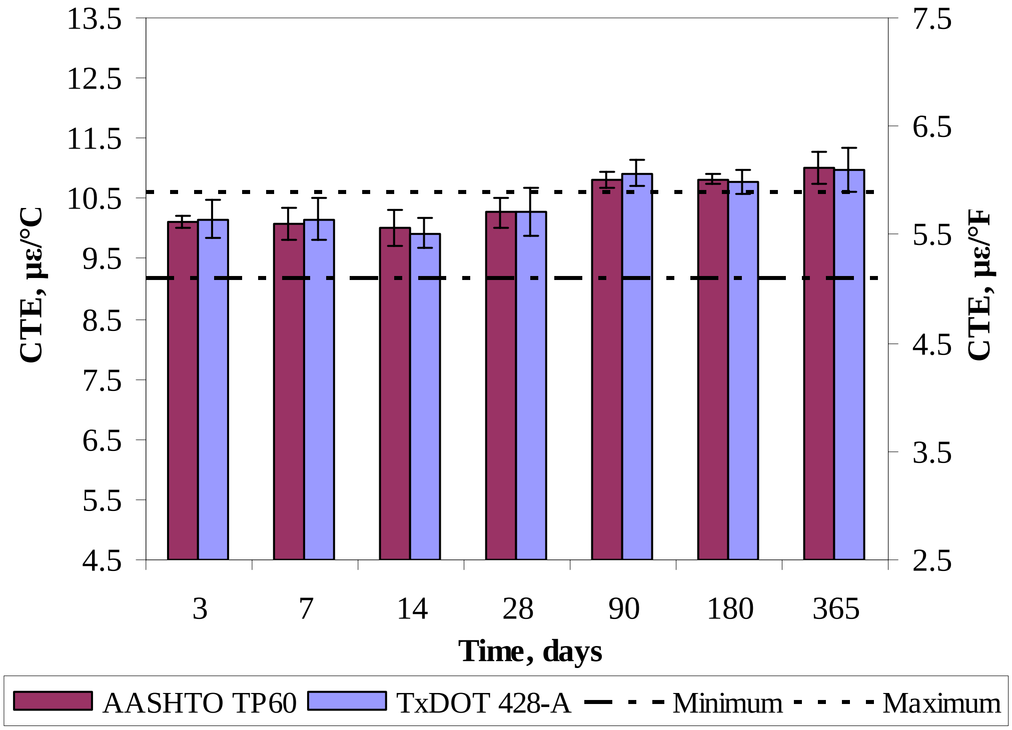


Figure 4-35. CTE 4 (Slag Concrete) Coefficient of Thermal Expansion

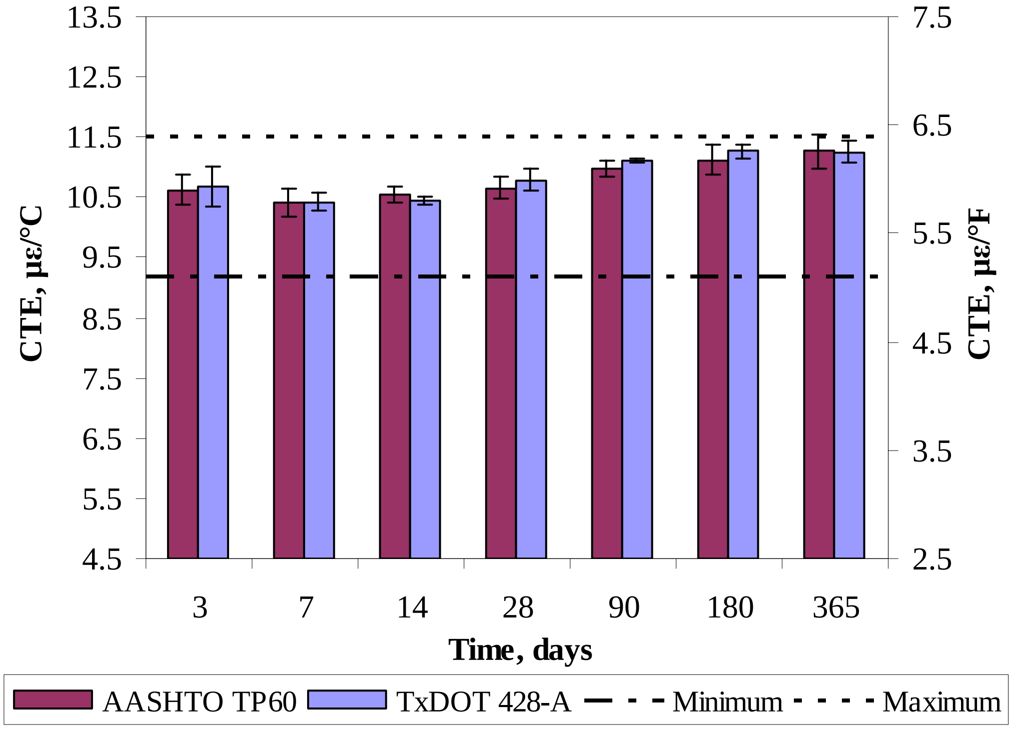


Figure 4-36. CTE 5 (Dolomite Concrete) Coefficient of Thermal Expansion

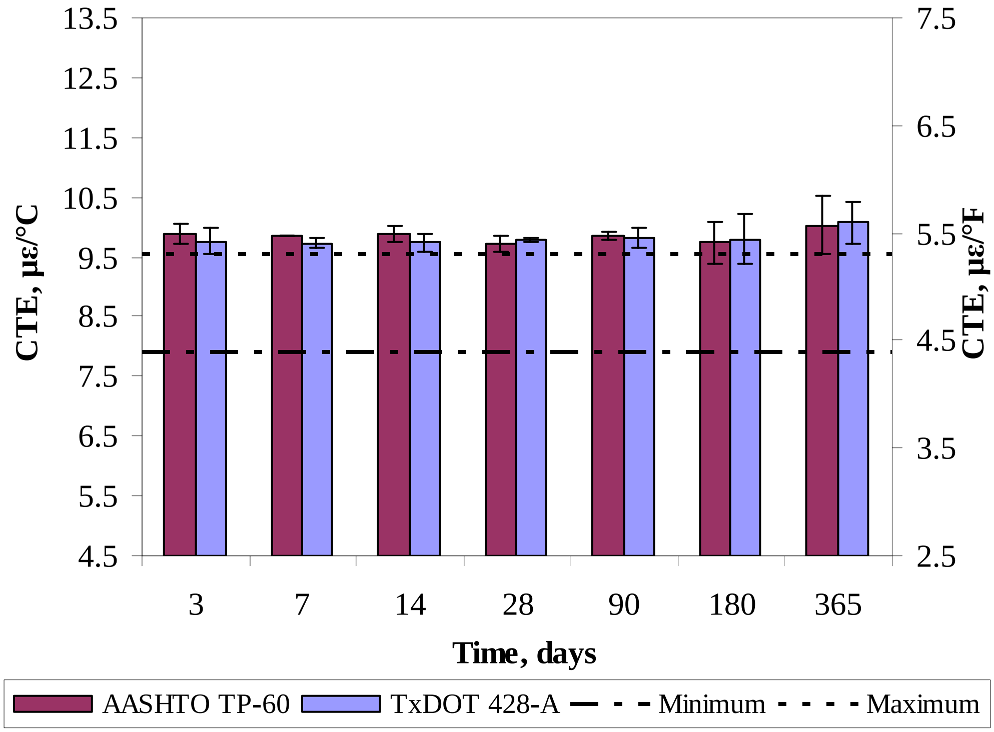


Figure 4-37. CTE 6 (Gabbro or Trap Rock Concrete) Coefficient of Thermal Expansion

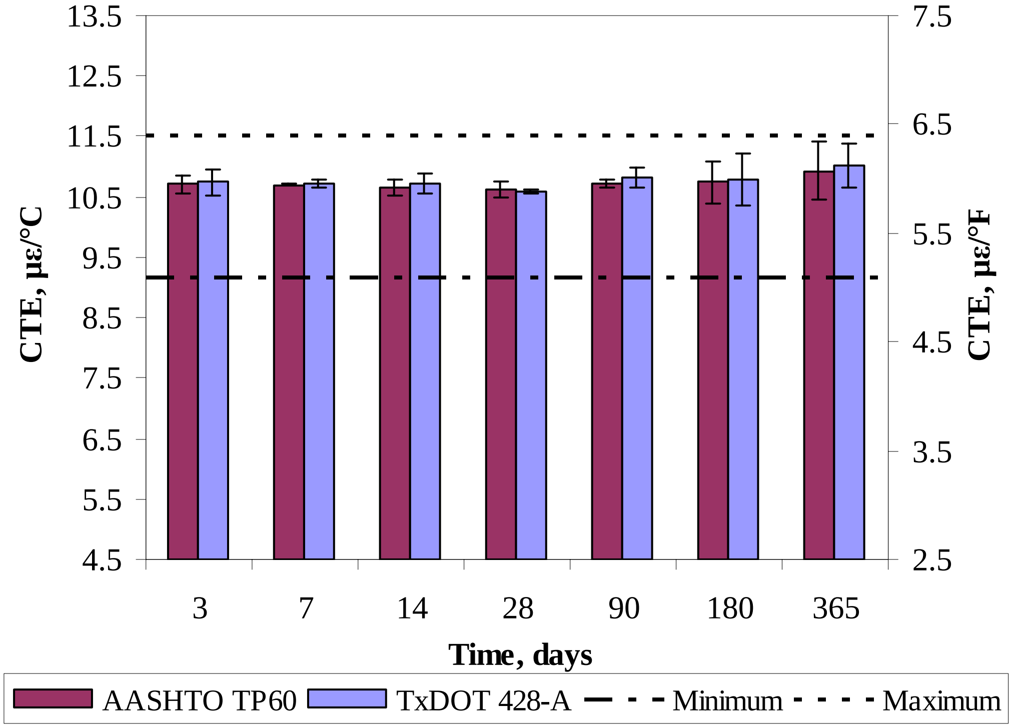


Figure 4-38. CTE 7 (Dolomite Concrete) Coefficient of Thermal Expansion

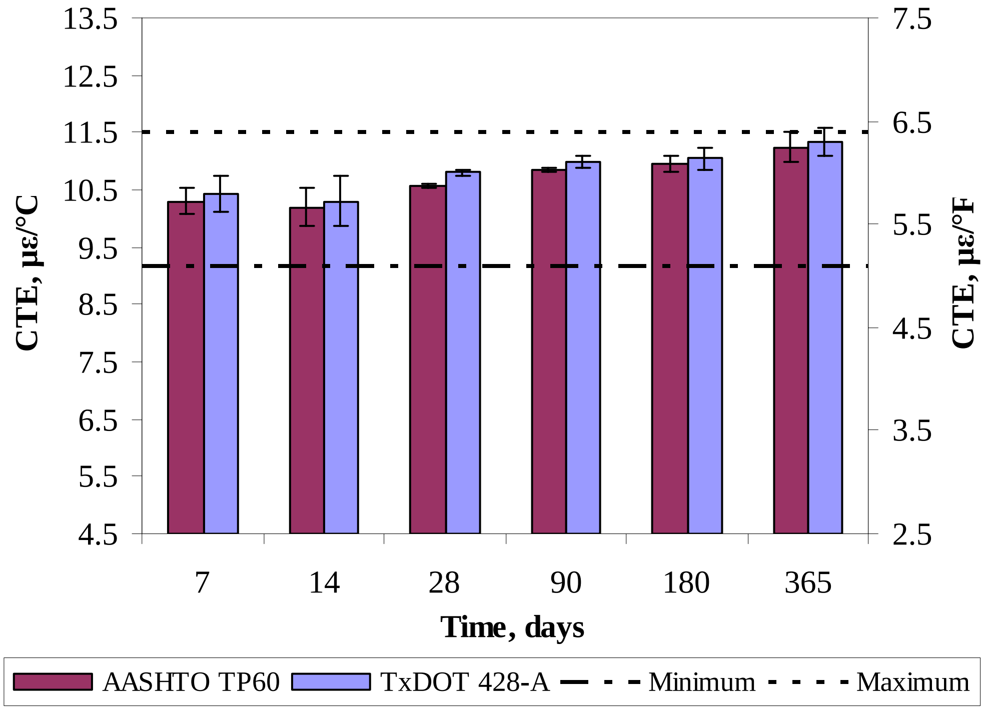


Figure 4-39. CTE 8 (Dolomite Concrete) Coefficient of Thermal Expansion

4.6 CTE Test Variability

The test variability (δ_{CTE}) was determined by subtracting the measured CTE within a batch (i.e. for a given mix ID and sample age) from the batch mean. Figure 4-40 illustrates the frequency histogram of δ_{CTE}. Approximately 98% of the data set has a δ_{CTE} between ± 0.3 µε/°F (0.5 µε/°C). The coefficient of variation ranges between 2.5% and 6%.The variability stems from a variety of factors including; (i) variable internal relative humidity in the sample at the time of testing; (ii) non-uniform temperature distribution in the sample; (iii) inhomogeneities in the specimen at the time of fabrication; (iv) LVDT sensitivity; (v) power fluctuations; and (vi) possible frame induced errors.

4.7 Statistical Analysis Approach

The factors that potentially affected the magnitude of the CTE in this experiment were aggregate geology, sample age, and number of heating-cooling cycles. To investigate the impact of these factors and their interactions on the magnitude of CTE, a "factorial treatment design" was employed. In a factorial treatment design, one factor, for example aggregate type, is tested over one or more other factors, for example sample age and number of heating-cooling cycles. Each factor has several categories called "levels". For example, levels of the sample age factor are 3, 7, 14, 28, 90, 180, and 365 days. The design factorial included, (i) aggregate geology with eight levels; (ii) sample age with seven levels and (iii) number of heating-cooling cycles with three levels. There were three replicate samples for each combination of aggregate geology and sample age. Table 4-5 shows the factorial design table.

Aggregate geology, sample age, and number of cycles were considered as fixed effects. In fixed effects, different levels of factors are reproducible. In other words if the experiment was to be repeated, the levels could be duplicated. Individual sample ID (replications) within each aggregate geology and sample age

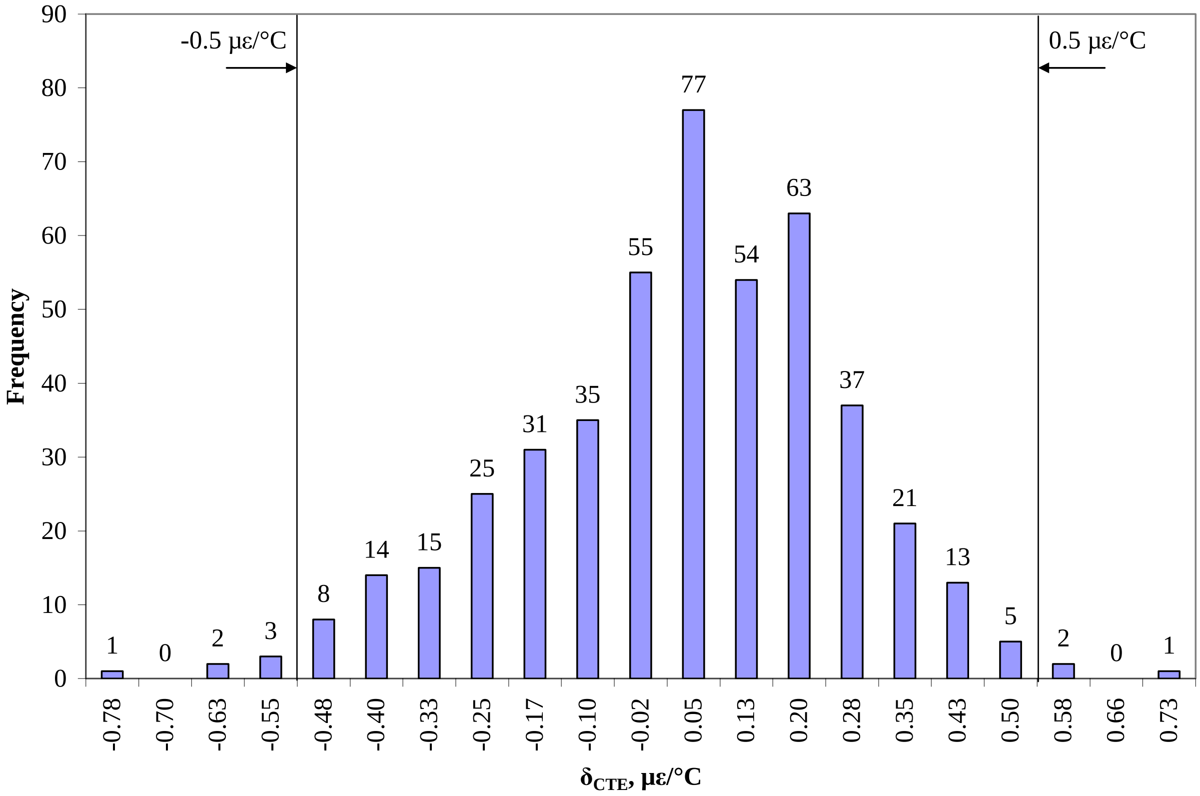


Figure 4-40. Variability Histogram

was considered as a random effect because for each combination of aggregate type and sample age, a sample ID was assigned randomly to the three replicates from the same batch of concrete. Additionally, the number of cycles were treated as repeated measurements of individual samples since multiple measurements (cycles) were taken on each of the replicate samples.

Since the experiment included both fixed and random effects, the statistical analysis was performed using the “mixed effect” models. The following general linear model describes the relationships between factors. The statistical significance of the factors and their interactions was evaluated by using the analysis of variance (ANOVA) method. *(20)*

y = μ + Agg_Type + Age + Agg_Type*Age + Sample_ID(Agg_Type Age) + Cycle + Agg_Type*Cycle + Age*Cycle + Agg_Type*Age*Cycle + e

where:

y = response variable which is the CTE value
μ = overall mean
Agg_Type = fixed effect of the aggregate geology
Age = fixed effect of the sample age at the time of testing
Agg_Type*Age = interaction effect of the aggregate geology and sample age
Sample_ID(Agg_Type Age) = random effect of the replications
Cycle = fixed effect of the cycle numbers
Agg_Type*Cycle = interaction effect of the aggregate geology and cycle numbers
Age*Cycle = interaction effect of the sample age and cycle numbers
Agg_Type*Age*Cycle = interaction effect of the aggregate geology, sample age, and cycle numbers
e = random experimental error

Table 4-5. Factorial Design Table*

Aggregate Geology	Number of Heating-Cooling Cycles	Age, Days							Total
		3	7	14	28	90	180	365	
CTE 1	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 2	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 3	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 4	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 5	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 6	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 7	1	X	X	X	X	X	X	X	7
	2	X	X	X	X	X	X	X	7
	3	X	X	X	X	X	X	X	7
CTE 8	1	N/A	X	X	X	X	X	X	6
	2	N/A	X	X	X	X	X	X	6
	3	N/A	X	X	X	X	X	X	6
Total		21	24	24	24	24	24	24	165

*Three replicates for each combination of factors were considered totaling the CTE values to 3*165=495

The first step in the analysis requires the checking of assumptions for the model. The assumptions require the residuals (difference between predicted and measured values) to be (i) independent, (ii) normally distributed, and (iii) having a common variance for all levels of each factor.

The independence assumption was evaluated based on the method by which the individual samples were chosen for testing. This assumption was satisfied because the samples were randomly selected for CTE measurement for each aggregate type and age.

The normality assumption was checked by inspection of the distribution of the residuals (histogram) and normal probability plot of the residuals after elimination of the outliers. The residual histogram should show a symmetric bell shaped distribution. The normal probability plot of the residuals should not deviate significantly from the straight line showed on the graph. Unusually high or low residuals were checked to determine whether those residuals were outliers or not. Raw data (measurements) of such residuals were checked to detect any equipment malfunction during that particular test cycle. The histogram and normal probability plot of the residuals for the entire dataset are illustrated in Figures 4-41 and 4-42 respectively.

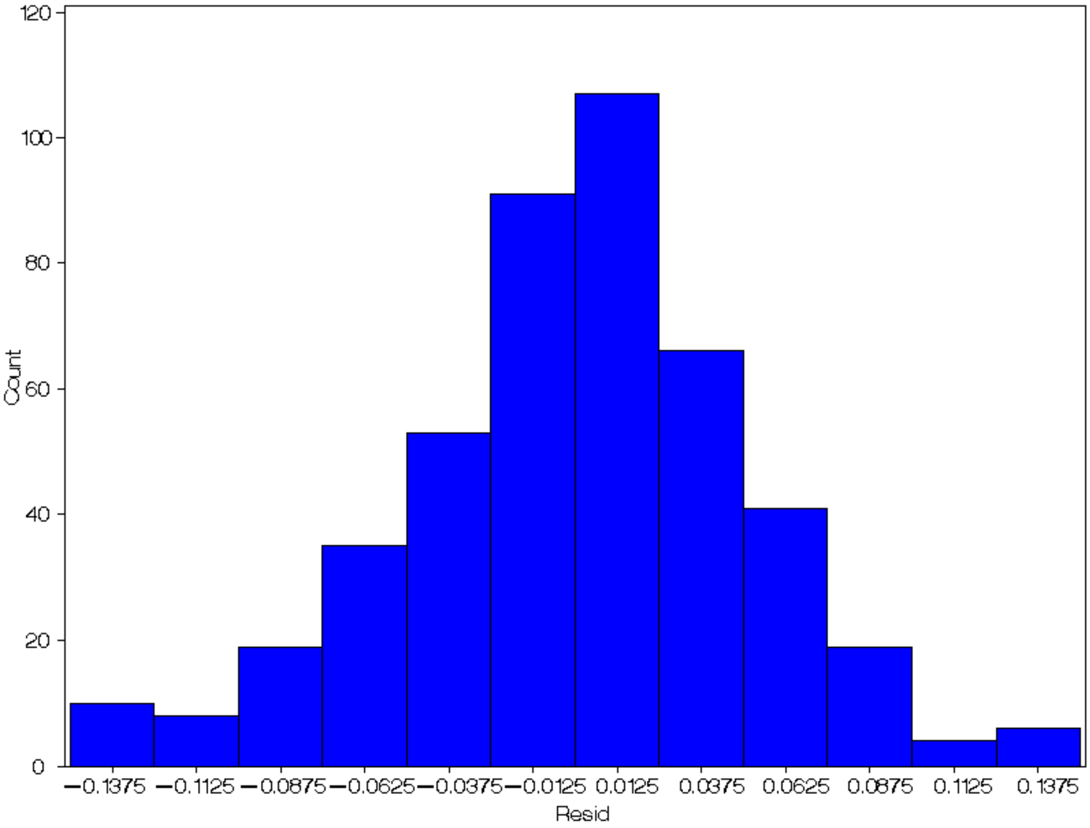


Figure 4-41. Histogram of the Residuals

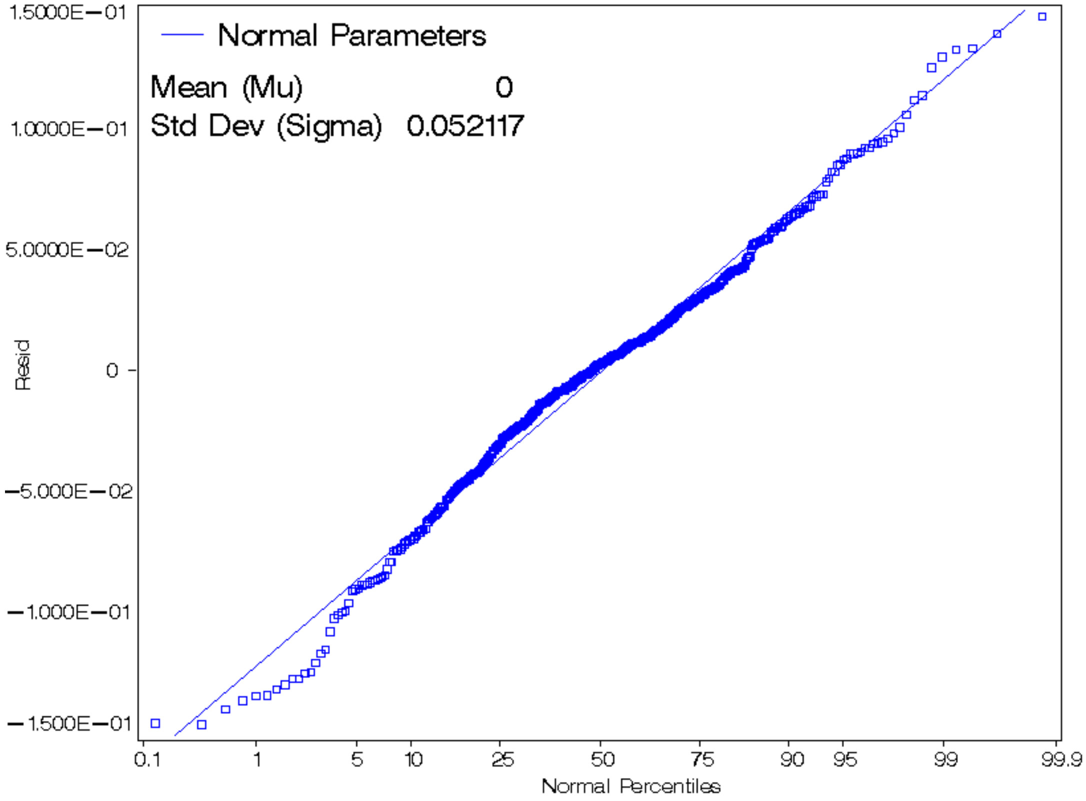


Figure 4-42. Normal Probability Plot of the Residuals

The homogeneity of the variances was assessed by examination of the variances of the residuals for all levels of each factor. Side-by-side box plots were employed to help in the identification of the largest and smallest variances. For this assumption to be valid, the ratio of the largest variance to the smallest variance should not exceed 3, 5, or 10. These limits are different rules of thumb and “5” was selected for this analysis. Side-by-side box plots of the residuals for different levels of “age” variable are shown in Figure 4-43. In this figure the median is represented by the horizontal line inside the box. The top and bottom of the box represent the 3rd quartile (75th percentile) and the 1st quartile (25th percentile), respectively. The distance between these two is the interquartile range (IQR). Whiskers are drawn to capture the minimum and maximum observations.

Based on the availability of the data for different comparisons and analyses, several datasets were used throughout the statistical analysis. For each dataset, the assumptions were checked and appropriate adjustments were made to the analyses where necessary.

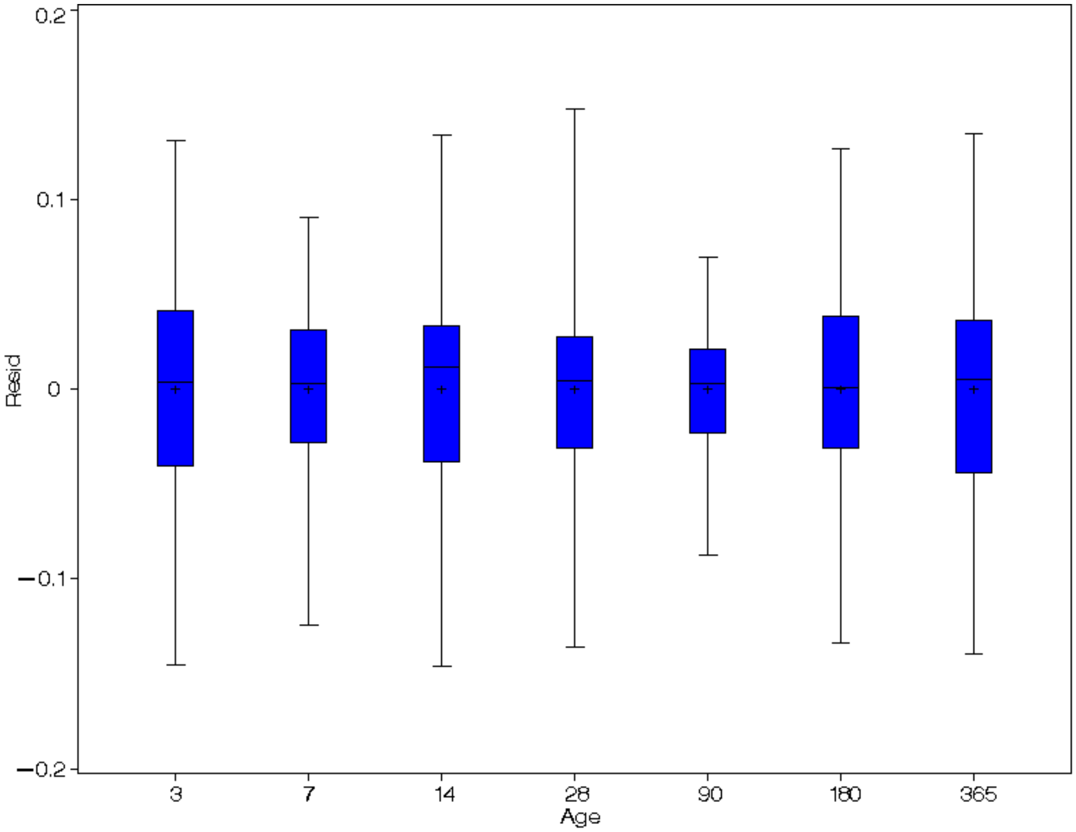


Figure 4-43. Side-By-Side Box Plots of the Residuals for Age Factor

After checking the assumptions, the significance of the factors, and their interactions were investigated. The Least Significant Difference (LSD) method was used for all-pairwise comparisons with an α value of 0.05. A main or interaction effect was considered significant if the p-value was less than 0.05.

The results from the mixed effects analysis are summarized in Table 4-6. The impact of aggregate geology, sample age and number of heating-cooling cycles on CTE is significant (P value less than 0.05). Furthermore, the interactions between (i) aggregate geology and sample age; and (ii) aggregate geology and number of heating-cooling cycles were found to be statistically significant.

Table 4-6. Tests of Fixed Effects

Effect	F Value	P Value
Aggregate Type	383.73	<.0001
Age	33	<.0001
Aggregate Type*Age	1.57	0.0338
Cycle Number	123.09	<.0001
Aggregate Type*Cycle Number	5.47	<.0001
Age*Cycle Number	1.42	0.1624
Aggregate Type*Age*Cycle Number	1.14	0.303

4.7.1 Aggregate Type Effect

Based on Table 4-6, aggregate type and its interaction with age and cycle number are significant (p-values less than 0.05). Therefore, the effect of aggregate type (or geology) on the magnitude of CTE must be investigated for each level of age and cycle number factors. This implies that concrete samples made with different types of coarse aggregate (different geologies) have different CTE values. This finding is in agreement with the results of other research (References 1, 2, 3, and 7).

4.7.2 Sample Age Effect

To investigate the effect of sample age at the time of test on CTE, the interaction effect of aggregate type and sample age was examined. This implies that the effect of age on CTE was investigated within each aggregate type. The variation in CTE as a function of sample age for all aggregate types is illustrated in Figure 4-43. Within each aggregate type shown in Figure 4-44 the column bars (representing average CTE) assigned the same letter are not significantly different from each other at a confidence level of 95%. Some column bars have two letters assigned to them. In the all-pairwise comparison, each level of age is compared to all other levels. For example, in CTE 1, 3-day CTE was compared to all other levels (showed by letter “a”). When 3-day CTE is different from 90-day CTE, this comparison is finished and a new comparison starts with 7-day CTE (denoted by letter “b”). Within each of the aggregate geologies, different column bars having the same letter indicate a group of ages which are statistically similar. If a column bar has two letters, it belongs to either one of the groups, but not both groups.

To study the impact of sample age within an aggregate type, an all-pairwise comparison using the LSD method was used. Based on the LSD analysis, it was found that for most aggregate types the magnitude of CTE at the end of 28 days was significantly different (lower) from the magnitude of CTE measured at the end of 90 to 365 days.

4.7.3 Number of Heating-Cooling Cycles Effect

A sample from each CTE mix design was subjected to three heating and cooling cycles to study the effect on CTE. In addition, since each mix design was using a different coarse aggregate source, the heating and cooling effect could be analyzed by aggregate type. The variability in CTE as a function of heating-cooling cycles is illustrated in Figure 4-45. Within each aggregate type shown in Figure 4-45 the column bars (representing average CTE) assigned the same letter are not significantly different from each other at a confidence level of 95%. The same discussion regarding the letters is also applicable to this analysis.

In most cases (except for CTE 6) the CTE determined at the end of the first heating-cooling cycle is significantly different (higher) than the CTE determined at the end of the second and third heating-cooling cycles. This conclusion was based on the results from an all-pairwise comparison using the LSD method. The same effect was observed in another study (Reference 7).

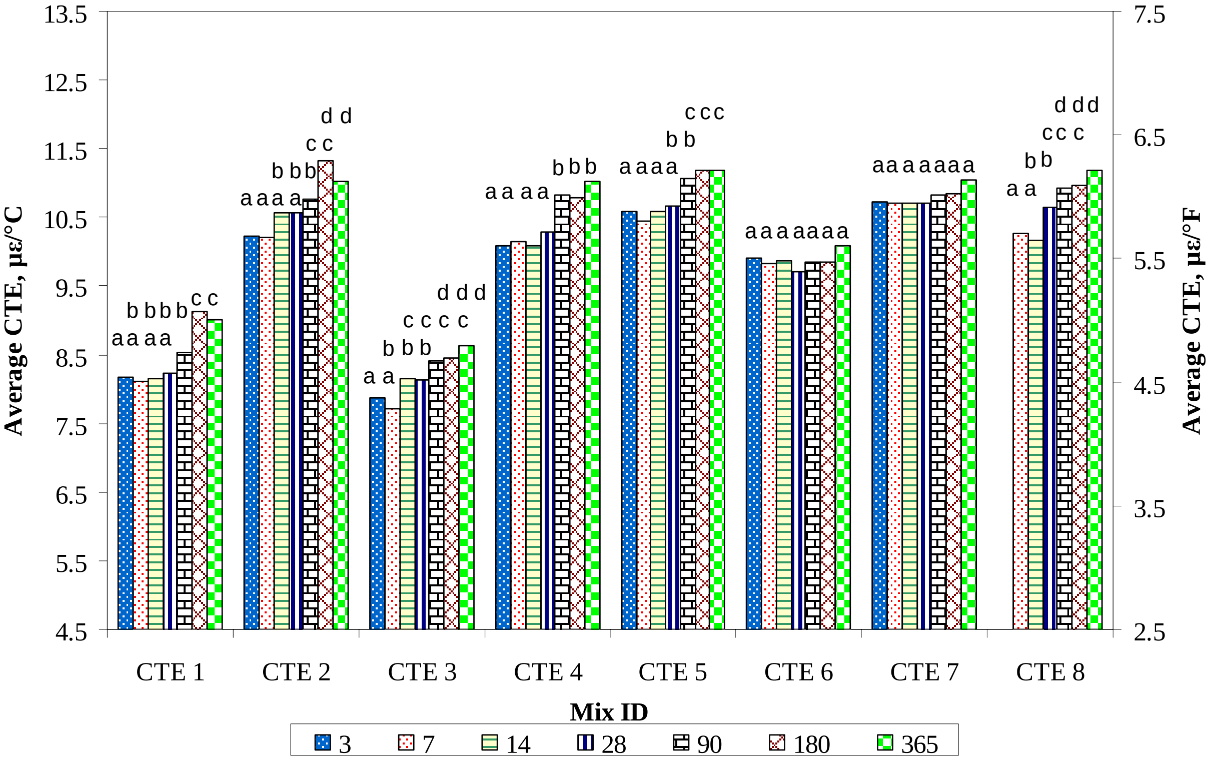


Figure 4-44. Average CTE for Various Aggregates as a Function of Test Specimen Age Based on 3 Replicates *

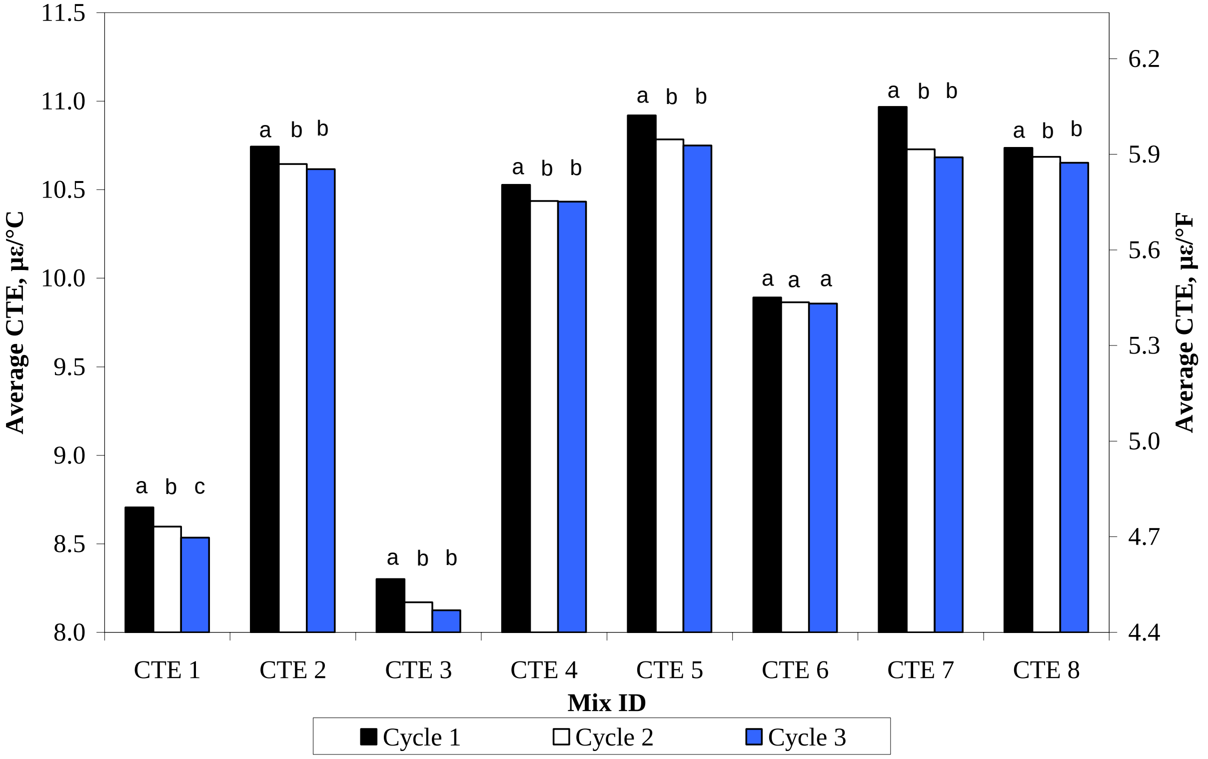


Figure 4-45. Average CTE for Various Aggregates as a Function of Number of Cycles Based on 3 Replicates *

*The column bars followed by the same letter within a CTE mix type are not significantly different.

4.8 Impact of CTE on Performance of Jointed Concrete Pavements

Sensitivity analyses were conducted to investigate the impact of CTE on the short-term (first 72-hours) effects using HIPERPAV II, and the long-term effects using the NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide (M-E PDG) software on the performance of jointed concrete pavements (JCP). CTE affects both thermally induced stresses within the pavement and joint movement. As a result, premature cracking, mid panel and corner cracking, faulting, and joint spalling can occur as mentioned. In order to minimize the occurrence of these distresses, the CTE value among other variables must be considered while designing a pavement. The performance parameter of interest for the short term effect was ratio of the maximum stress in concrete slab to PCC strength. The performance parameter of interest for the long term effect was transverse cracking. Tables 4-7 and 4-9 summarize the sensitivity matrices used to investigate the short and long-term effects of CTE on the performance of JCPs.

4.8.1 Short Term Effects Analysis

A factorial was developed to investigate the effects of CTE on the early age of the concrete pavement. The details about the variables and levels used in the sensitivity analysis are summarized in Table 4-7. In addition, CTE values for each type of aggregate were the maximum, the minimum, and the average measured values. Levels of modulus of rupture were maximum, minimum, and average tested values. Actual mixture design proportions were used as inputs. Splitting tensile strength and elastic modulus were obtained from laboratory test data. Also, laboratory measured maturity data were used as inputs. The initial PCC mixture temperature was assumed to be 75 °F for all mix designs.

All the HIPERPAV II runs were completed and the generated data were analyzed. An example of the data synthesis is summarized in Table 4-8 and Figures 4-46 and 4-47. Since the HIPERPAV II analysis was done on a “specification” paving mixture design, the potential of early age cracking (within 72 hours after construction) is minimal. The key outputs of interest were tensile stress and strength of the pavement.

By examining Figure 4-46, it can be seen that for CTE 1, the design with thinner slab, longer joint spacing, and high CTE (design 2), the curves representing slab stresses and PCC strength are closer to each other which is an indication of performance issues as compared with design 1. This can also be seen from last column in Table 4-8 which shows a higher ratio of maximum stress to PCC strength for design 2 in comparison with design 1. A similar trend can be seen in CTE 8 designs (Figure 4-47). In general pavements made with these approved mix designs did not show any practical sensitivity to the magnitude of the PCC CTE.

Table 4-7. Sensitive Input Variables for HIPERPAV II*

Cluster		Variables	Levels	Remarks
Design		• Joint Spacing (ft)	12’ , 15’, 20’	3 Levels
		• Dowel Diameter (in)	1.25” (for 9” slab) 1.5” (for 14” slab)	Fixed
		• Slab Width (ft)	12’ vs. 14’	2 Levels
Materials	PCC	• PCC Slab Thickness	9” vs. 14”	2 Levels
		• CTE	-	3 Levels based on measured values
		• f'_c (Compressive Strength, psi)	-	Measured values
		• MOR (Modulus of Rupture, psi)	-	3 Levels based on measured values
		• Elastic Modulus (psi)	-	Measured values
		• Split Tensile Strength	-	Measured values
	Base	• Base Type	Granular Base (DGAB)	Fixed
		• Base Thickness (in)	4”	Fixed
	Subbase	• Subbase Type	Sand	Fixed
		• Subbase Thickness (in)	16”	Fixed
	Subgrade	• Soil Type	A-7-6 (fine)	Fixed
Construction		• Curing Method	Single Coat vs. Double Coat	2 Levels
Environmental		• Climatic Region	Lansing	Fixed

*3 Joint spacings * 2 Slab widths * 2 Slab thicknesses * 3 CTE values * 3 MOR levels * 2 Curing methods * 8 Aggregate types = 1728 Runs

Table 4-8. Example of HIPERPAV II Sensitivity Analysis

Mix ID	Design	ST (in)	JS (ft)	SW (ft)	Coat	Split Tensile Strength (psi)	CTE με/ºF (με/ºC)	Max. Stress (psi)	Time (hr)	PCC Strength (psi)	Max. Stress/PCC Strength
CTE 1	1	14	12	12	SC	28-Day (516)	Min 4.42 (7.96)	28.7	43	284.6	0.1008
	2	9	20	14	SC	Min (471)	Max 5.08 (9.15)	71	50	281.7	0.2520
CTE 8	1	14	12	12	SC	Max (587)	Min 5.46 (9.83)	28.6	42	182.8	0.1565
	2	9	20	14	SC	Min (471)	Max 6.04 (10.87)	80	50	147.9	0.5409

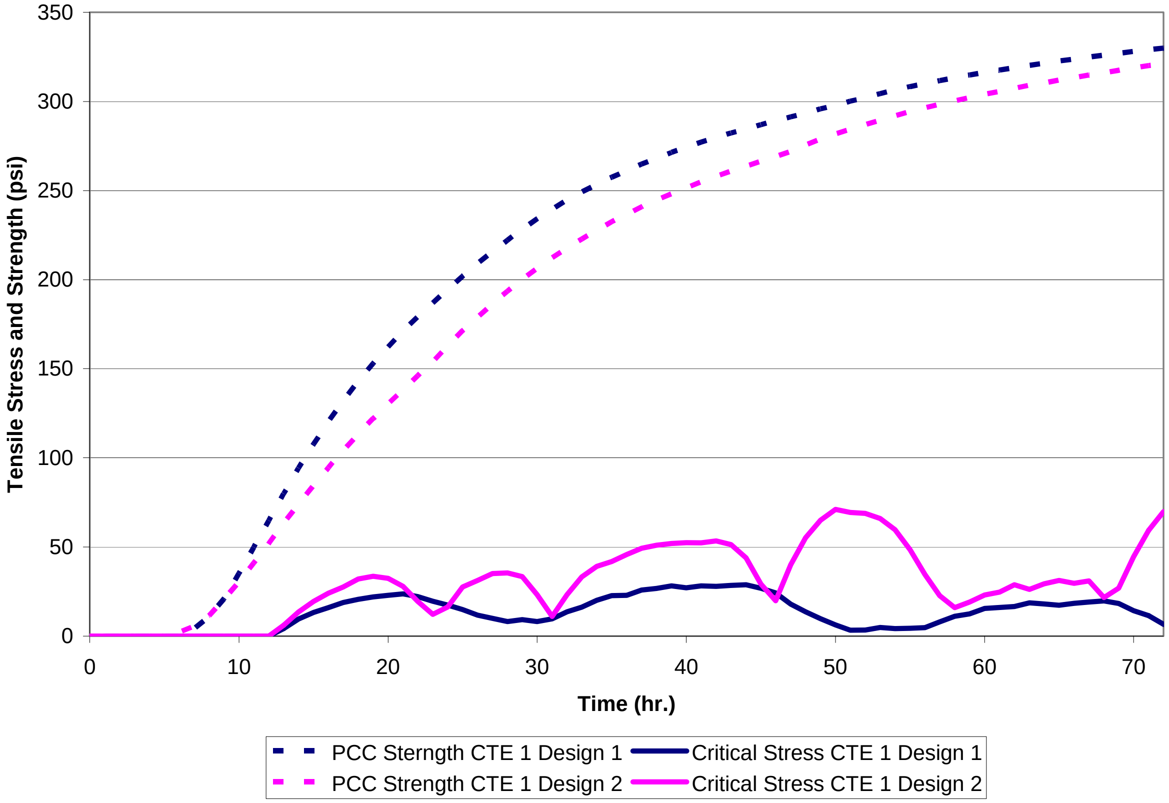


Figure 4-46. Example HIPERPAV II Plot (CTE 1)

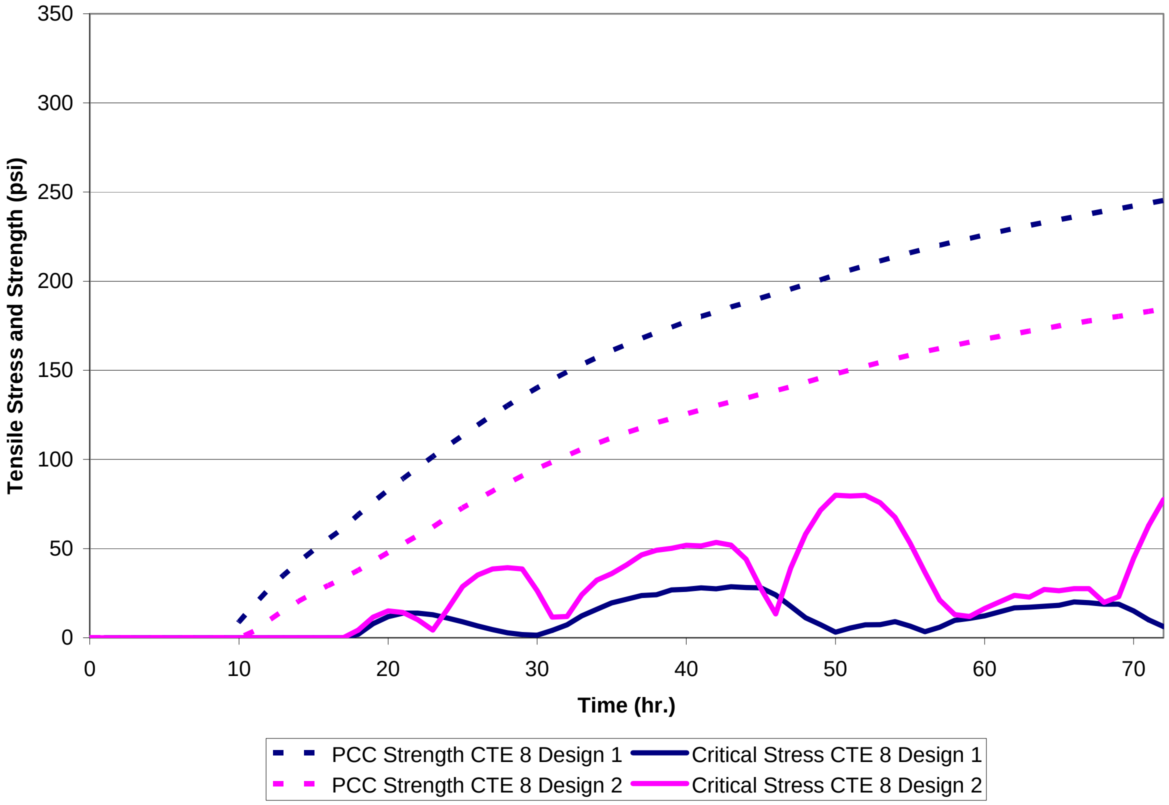


Figure 4-47. Example HIPERPAV II Plot (CTE 8)

4.8.2 Long Term Effects Analysis

Five set of analyses were conducted to investigate the effects of CTE on the long term performance of JCPs:

- The effect of CTE test variability on cracking performance of the concrete pavement;
- The effect of CTE of concrete made with different aggregate types on cracking performance of the pavement;
- The effect of CTE based on different test cycles on cracking performance of the concrete pavement;
- The effect of CTE at different ages on cracking performance of the concrete pavement; and
- The effect of CTE, joint spacing, slab thickness, and their interactions on cracking performance of the concrete pavement

To investigate the effect of CTE test variability on pavement performance, a sample pavement with 15 ft. joint spacing and 10 in. slab thickness was considered. The slab was placed on a 4 in. thick granular base and 16 in. sand subbase. The subgrade was a fine A-7-6 soil which is a clayey soil with greater than 35% passing the #200 sieve, minimum liquid limit of 41, and minimum plasticity index of 41 (based on AASHTO soil classification). Other inputs are summarized in Table 4-9. Two types of concrete were considered. One made with limestone which had a low CTE. Two levels of CTE values equal to 4.60 and 4.91 με/ºF (8.28 and 8.84 με/ºC) with a difference of 0.31 με/ºF (0.56 με/ºC) were also considered. The other concrete considered was made with dolomite with CTE values of 5.87 and 6.18 με/ºF (10.56 and 11.12 με/ºC) with the same magnitude for the difference. The results of the M-E PDG software showed that although both concrete mixtures had the same difference between their CTE values, the concrete with higher CTE (dolomite) is more sensitive to the CTE variability (percent slabs cracked after 30 years changes from 20.7 to 38%) than the concrete with low CTE which showed almost no change in percent slabs cracked after 30 years (0 to 0.1%). The same effect was observed in the research reported in reference 6. Figure 4-48 shows this effect. It should be mentioned that both designs were identical except for the aggregate type used in concrete. The difference in performance is due to difference in CTE values plus the strength of the concrete which depends among other factors, on the aggregate type.

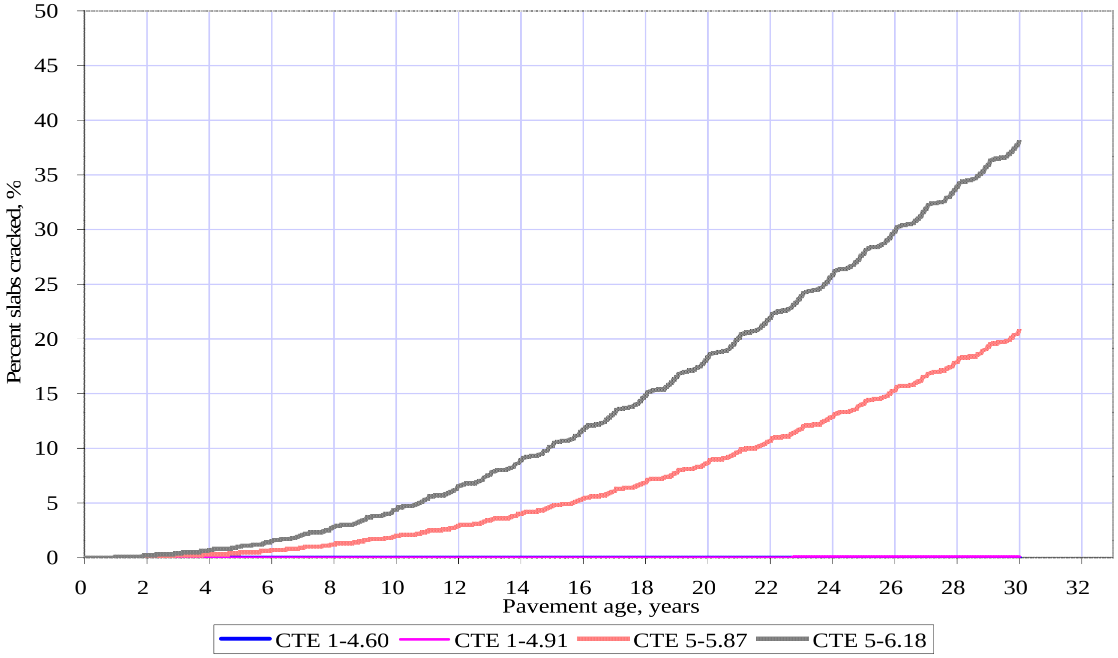


Figure 4-48. Percent Slabs Cracked for CTE Test Variability

Table 4-9. Sensitive Input Variables for M-E PDG*

Cluster		Variables	Levels	Remarks
Design		• Joint Spacing (ft)	12’ , 15’, 20’	3 Levels
		• Edge Support	Tied Shoulders	Fixed
		• Dowel Diameter (in)	1.25” (for 9” slab) 1.5” (for 14” slab)	Fixed
		• Dowel Spacing (in)	12”	Fixed
		• Slab Width (ft)	12’ vs. 14’	2 Levels
Materials	PCC	• PCC Slab Thickness	9” vs. 14”	2 Levels
		• CTE	-	3 Levels based on measured values
		• *fc’* (Compressive Strength, psi)	-	Measured values
		• MOR (Modulus of Rupture, psi)	-	Measured values
		• Elastic Modulus (psi)	-	Measured values
		• Split Tensile Strength	-	Measured values
	Base	• Base Type	Granular Base (DGAB)	Fixed
		• Base Thickness (in)	4”	Fixed
	Subbase	• Subbase Type	Sand	Fixed
		• Subbase Thickness (in)	16”	Fixed
	Subgrade	• Soil Type	A-7-6 (fine)	Fixed
Environmental		• Climatic Region	Lansing	Fixed

*3 Joint spacings * 2 Slab widths * 2 Slab thicknesses * 3 CTE values * 8 Aggregate types = 288 Runs

A sensitivity analysis was conducted on the same concrete slab to investigate the effect of geology on pavement performance. The only variable in this analysis was the coarse aggregate type. Strength properties and CTE values resulted from laboratory testing were used in the analysis. So, the only differences between mixes were hardened concrete properties (for example strength and elastic moduli) and CTE values. Average CTE values for each aggregate type were used. The results are presented in Table 4-10. It clearly shows the different percent slabs cracked for different aggregate types.

The effect of number of cycles on pavement performance was investigated based on the same slab mentioned before. Table 4-11 presents the results. It does not seem to have a practical effect on pavement performance. The maximum change in percent slabs cracked after 30 years was 2.1%. Generally, the percent slabs cracked based on the first cycle is higher than other cycles. In addition, it can be observed that the results based on second and third cycles are closer to each other.

Table 4-10. Percent Slabs Cracked Based on CTE Values for Different Aggregate Types

Mix ID	Aggregate Type	CTE, με/ºF	CTE, με/ºC	Pavement Age, Years			
				5	10	20	30
CTE 1	Limestone	4.75	8.55	0	0	0	0
CTE 2	Gravel	5.93	10.67	0.1	0.7	4.3	13.2
CTE 3	Dolomitic Limestone	4.56	8.21	0	0	0.1	0.3
CTE 4	Slag	5.81	10.46	0	0	0	0
CTE 5	Dolomite	6.01	10.82	0.4	1.3	4	7.8
CTE 6	Gabbro (Trap Rock)	5.48	9.86	0	0.2	1.1	3.7
CTE 7	Dolomite	6.00	10.80	0	0	0	0
CTE 8	Dolomite	5.96	10.73	0.1	0.5	2.8	8.3

Table 4-11. Percent Slabs Cracked Based on CTE Values for Different Cycles

Mix ID	Cycle Number	CTE, με/ºF	CTE, με/ºC	Pavement Age, Years				Comments
				5	10	20	30	
CTE 1	1	4.84	8.71	0	0	0	0	Number of cycles does not have an effect on this mix.
	2	4.78	8.60	0	0	0	0	
	3	4.74	8.53	0	0	0	0	
CTE 2	1	5.97	10.75	0.1	0.8	4.8	14.4	There is a maximum of 2.1% difference in % slabs cracked after 30 years for this mix.
	2	5.891	10.60	0.1	0.7	4.1	12.6	
	3	5.90	10.62	0.1	0.6	4.0	12.3	
CTE 3	1	4.61	8.30	0	0	0.1	0.4	Number of cycles has a very small effect on this mix (0.1%).
	2	4.54	8.17	0	0	0.1	0.3	
	3	4.51	8.12	0	0	0.1	0.3	
CTE 4	1	5.88	10.58	0	0	0	0	Number of cycles does not have an effect on this mix.
	2	5.80	10.44	0	0	0	0	
	3	5.80	10.44	0	0	0	0	
CTE 5	1	6.07	10.93	0.5	1.5	4.6	8.9	There is a maximum of 1.9% difference in % slabs cracked after 30 years for this mix.
	2	5.99	10.78	0.4	1.2	3.7	7.3	
	3	5.97	10.75	0.4	1.2	3.6	7	
CTE 6	1	5.50	9.90	0	0.2	1.2	3.9	Number of cycles has a very small (0.2%) effect on % slabs cracked.
	2	5.48	9.86	0	0.2	1.1	3.7	
	3	5.48	9.86	0	0.2	1.1	3.7	
CTE 7	1	6.09	10.96	0	0	0	0	Number of cycles does not have an effect on this mix.
	2	5.96	10.73	0	0	0	0	
	3	5.94	10.69	0	0	0	0	
CTE 8	1	5.96	10.73	0.1	0.5	2.8	8.3	There is a maximum of 0.8% difference in % slabs cracked after 30 years for this mix.
	2	5.94	10.69	0.1	0.4	2.6	7.9	
	3	5.92	10.66	0.1	0.4	2.5	7.5	

For the analysis regarding impact of CTE of concrete with different ages on pavement performance, the same pavement mentioned before was considered. For each of the aggregate types, average CTE values at 14, 28, and 90 days were selected. The results of the M-E PDG analysis are shown in Table 4-12. The difference in percent slabs cracked ranged from 0 to 6.1% after 30 years. The overall effect of CTE on percent slabs cracked based on the results does not seem to be significant (operational) for this typical design. Based on this limited analysis, the author recommends the measurement of CTE at 28 days to be considered in pavement design.

Table 4-12. Percent Slabs Cracked Based on CTE Values for Different Ages

Mix ID	Age, Days	CTE, με/ºF	CTE, με/ºC	Pavement Age, Years				Comments
				5	10	20	30	
CTE 1	14	4.52	8.13	0	0	0	0	Age at the time of testing does not have an effect on this mix.
	28	4.54	8.18	0	0	0	0	
	90	4.77	8.59	0	0	0	0	
CTE 2	14	5.87	10.57	0.1	0.6	3.7	11.5	There is a maximum of 3.5% difference in % slabs cracked after 30 years for this mix.
	28	5.84	10.52	0.1	0.5	3.4	10.7	
	90	5.96	10.73	0.1	0.8	4.7	14.2	
CTE 3	14	4.50	8.10	0	0	0.1	0.3	Age at the time of testing does not have an effect on this mix.
	28	4.51	8.11	0	0	0.1	0.3	
	90	4.56	8.21	0	0	0.1	0.3	
CTE 4	14	5.56	10.01	0	0	0	0	Age at the time of testing does not have an effect on this mix.
	28	5.71	10.27	0	0	0	0	
	90	6.01	10.81	0	0	0	0	
CTE 5	14	5.86	10.55	0.3	0.9	2.7	5.2	There is a maximum of 4.6% difference in % slabs cracked after 30 years for this mix.
	28	5.92	10.65	0.3	1	3.2	6.2	
	90	6.11	10.99	0.5	1.7	5	9.8	
CTE 6	14	5.49	9.89	0	0.2	1.1	3.8	Age at the time of testing has a very small (0.8%) effect on % slabs cracked.
	28	5.41	9.73	0	0.1	0.9	3	
	90	5.47	9.85	0	0.2	1.1	3.6	
CTE 7	14	5.92	10.65	0	0	0	0	Age at the time of testing does not have an effect on this mix.
	28	5.90	10.62	0	0	0	0	
	90	5.96	10.73	0	0	0	0	
CTE 8	14	5.66	10.19	0	0.2	1.1	3.5	There is a maximum of 6.1% difference in % slabs cracked after 30 years for this mix.
	28	5.87	10.57	0.1	0.3	2.1	6.4	
	90	6.02	10.84	0.1	0.5	3.2	9.6	

For the last analysis, a factorial (as shown in Table 4-9) was developed to investigate the effects of CTE and other design features on the long term performance of the concrete pavement. The details about the variables and levels used in the sensitivity analysis are summarized in Table 4-9. CTE values for each type of aggregate were the maximum, the minimum, and the average measured values. Actual mix design proportions were used as inputs. Elastic modulus and modulus of rupture values were obtained from laboratory tests. Initial two-way average annual daily truck traffic (AADTT) was considered to be 6000.

In order to investigate the effect of the variables presented in Table 4-9 on performance of concrete pavement (cracking), an analysis of variance (ANOVA) was performed on each set of designs with same aggregate type. Based on the outcome of these analyses, the statistical significance of different variables and their interactions were obtained. A variable or an interaction is statistically significant if the p-value is less than 0.05 (a confidence level of 95%). The practical significance (is defined in the subsequent paragraphs) of the significant variables was then studied. Here, only the variables with both statistical and practical significance were selected for the investigation. The results (ANOVA, main effect, and interaction effect tables) are shown in Tables 4-14 to 4-21. Variables and interactions that are both statistically and practically significant are highlighted in the ANOVA tables and are presented in the interaction effect tables. Δ_{MAX} in the main and interaction effect tables (tables b and c for each aggregate type) is the maximum difference in percent slabs cracked for the given levels of the variables.

The main effects show the impact of a particular variable on percent slabs cracked for a given number of years (age of the pavement). The interaction effects show the effect of a combination of two or three variables on pavement cracking. The Federal Highway Administration (FHWA) has specified percent slabs cracked at the end of 5, 10, 20, and 30 years of rigid pavement age for two levels of criteria (good to normal and normal to poor) *(21)*. These criteria are shown in Table 4-13. In this table, Δ is the difference in percent slabs cracked between two criteria levels. The same approach was used to produce following tables in order to investigate the effects on cracking performance. The practical significance was investigated by comparing the percent slabs cracked with specified FHWA values.

It can be seen from these tables that, thinner slab, longer joint spacing, and higher CTE values lead to increased percent of slabs cracked over the age of a pavement. It can also be seen from a number of analyses that when comparing the effect of CTE combined with the effect of slab thickness or joint spacing, the combined effect of CTE and joint spacing is more significant than the effect of CTE and slab thickness based on the investigated levels.

Table 4-13. FHWA Cracking Criteria for Rigid Pavements *(21)*

Performance Measure	Criteria	Pavement Age (years)				
		0	5	10	20	30
Cracking (% Slabs Cracked)	Good-Normal	0	1.25	2.5	5	7.5
	Normal-Poor	0	2.5	5	10	15
	Δ	0	1.25	2.5	5	7.5
	Increase/year		0.5	0.5	0.5	0.5
	Average Increase/year	0.5				

Abbreviations used in the following tables are:

ST = Slab thickness, JS = Joint spacing, SW = Slab width, CTE = Coefficient of thermal expansion

Table 4-14 a. CTE 1 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	4.6225	4.6225	8.03	0.0298
JS	2	9.245	4.6225	8.03	0.0201
SW	1	1.5625	1.5625	2.71	0.1506
CTE	2	4.265	2.1325	3.7	0.0896
ST*JS	2	9.245	4.6225	8.03	0.0201
ST*SW	1	1.5625	1.5625	2.71	0.1506
ST*CTE	2	4.265	2.1325	3.7	0.0896
JS*SW	2	3.125	1.5625	2.71	0.1448
JS*CTE	4	8.53	2.1325	3.7	0.0751
SW*CTE	2	1.15166667	0.57583333	1	0.4219
ST*JS*SW	2	3.125	1.5625	2.71	0.1448
ST*JS*CTE	4	8.53	2.1325	3.7	0.0751
JS*SW*CTE	4	2.30333333	0.57583333	1	0.4752

Table 4-14 b. CTE 1 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0	0	0	0	0.02	0.07	0.29	0.72
	9	0.02	0.07	0.29	0.72				
Joint Spacing (ft)	12	0	0	0	0	0.03	0.11	0.43	1.08
	15	0	0	0	0				
	20	0.03	0.11	0.43	1.08				
Slab Width (ft)	14	0.01	0.01	0.06	0.15	0.01	0.05	0.18	0.42
	12	0.02	0.06	0.23	0.57				
CTE, με/˚F (με/˚C)	4.42 (7.96)	0	0.01	0.03	0.07	0.03	0.08	0.32	0.78
	4.69 (8.44)	0.01	0.02	0.07	0.17				
	5.12 (9.22)	0.03	0.08	0.34	0.84				

Table 4-15 a. CTE 2 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	10441.43361	10441.43361	612.65	<.0001
JS	2	26380.04056	13190.02028	773.92	<.0001
SW	1	294.1225	294.1225	17.26	0.006
CTE	2	1833.67056	916.83528	53.8	0.0001
ST*JS	2	7658.53389	3829.26694	224.68	<.0001
ST*SW	1	55.00694	55.00694	3.23	0.1225
ST*CTE	2	6.22056	3.11028	0.18	0.8376
JS*SW	2	173.015	86.5075	5.08	0.0513
JS*CTE	4	841.24444	210.31111	12.34	0.0047
SW*CTE	2	59.735	29.8675	1.75	0.2515
ST*JS*SW	2	393.63722	196.81861	11.55	0.0088
ST*JS*CTE	4	2562.82444	640.70611	37.59	0.0002
JS*SW*CTE	4	29.92	7.48	0.44	0.7775

Table 4-15 b. CTE 2 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0.19	0.93	4.37	9.23	22.37	29.83	33.02	34.06
	9	22.56	30.77	37.39	43.29				
Joint Spacing (ft)	12	0	0.03	0.14	0.47	33.86	46.13	55.6	63.19
	15	0.28	1.37	6.76	14.67				
	20	33.86	46.16	55.74	63.66				
Slab Width (ft)	14	9.93	14.7	19.04	23.41	2.9	2.3	3.68	5.72
	12	12.83	17	22.72	29.12				
CTE, με/˚F (με/˚C)	5.29 (9.52)	5.74	12.56	16.51	18.18	10	6.03	9.87	17.36
	5.91 (10.64)	12.65	16.41	19.76	25.07				
	6.42 (11.56)	15.74	18.58	26.38	35.54				

Table 4-15 c. CTE 2 Interaction Effects

Variables			ST, CTE Level	JS, ST Level		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST		JS	14		12	0	0	0	0	0.583	2.8	13.12	27.7
					15	0	0	0	0				
					20	0.58	2.8	13.12	27.7				
			9		12	0	0.05	0.283	0.93	67.13	89.47	98.08	98.68
					15	0.55	2.73	13.52	29.3				
					20	67.13	89.52	98.37	99.6				
CTE		JS	5.29 (9.52)		12	0.00	0.00	0.03	0.08	17.18	37.48	48.35	50.88
					15	0.05	0.20	1.13	3.53				
					20	17.18	37.48	48.38	50.95				
			5.91 (10.64)		12	0.00	0.03	0.10	0.33	37.78	48.25	53.85	61.08
					15	0.18	0.93	5.23	13.48				
					20	37.78	48.28	53.95	61.40				
			6.42 (11.56)		12	0.00	0.05	0.30	1.00	46.63	52.68	64.60	77.63
					15	0.60	2.98	13.93	27.00				
					20	46.63	52.73	64.90	78.63				
CTE	ST	JS	5.29 (9.52)	14	12	0	0	0	0	0	0.15	0.45	0.95
					15	0	0	0	0				
					20	0	0.15	0.95	2.95				
				9	12	0	0	0.05	0.15	34.4	74.8	90.2	95.75
					15	0.1	0.4	2.25	7.05				
					20	34.35	74.8	95.8	98.95				
			5.91 (10.64)	14	12	0	0	0	0	0.3	1.5	4.1	8.5
					15	0	0	0	0				
					20	0.3	1.5	8.5	22.9				
				9	12	0	0.05	0.2	0.65	75.3	95	98.4	99.2
					15	0.35	1.85	10.45	26.95				
					20	75.25	95.05	99.4	99.9				
			6.42 (11.56)	14	12	0	0	0	0	1.45	6.75	16.6	29.9
					15	0	0	0	0				
					20	1.45	6.75	29.9	57.25				
				9	12	0	0.1	0.6	2	91.8	98.6	99.3	99.3
					15	1.2	5.95	27.85	54				
					20	91.8	98.7	99.9	100				

Table 4-16 a. CTE 3 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	7321.65444	7321.65444	199.9	<.0001
JS	2	12859.29389	6429.64694	175.54	<.0001
SW	1	202.58778	202.58778	5.53	0.0569
CTE	2	360.98722	180.49361	4.93	0.0542
ST*JS	2	12519.77389	6259.88694	170.91	<.0001
ST*SW	1	191.36111	191.36111	5.22	0.0623
ST*CTE	2	324.72056	162.36028	4.43	0.0658
JS*SW	2	173.11056	86.55528	2.36	0.175
JS*CTE	4	547.80444	136.95111	3.74	0.0737
SW*CTE	2	47.68722	23.84361	0.65	0.5548
ST*JS*SW	2	159.25722	79.62861	2.17	0.1949
ST*JS*CTE	4	489.35111	122.33778	3.34	0.0914
JS*SW*CTE	4	153.91444	38.47861	1.05	0.4548

Table 4-16 b. CTE 3 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0	0.01	0.06	0.18	3.02	10.31	21.86	28.52
	9	3.02	10.31	21.91	28.7				
Joint Spacing (ft)	12	0	0	0.03	0.08	4.5	15.33	32.18	41.07
	15	0.03	0.14	0.73	2.1				
	20	4.5	15.33	32.2	41.14				
Slab Width (ft)	14	0.74	3.38	8.68	12.07	1.54	3.55	4.61	4.74
	12	2.28	6.93	13.29	16.81				
CTE, με/˚F (με/˚C)	4.10 (7.38)	0.28	1.19	5.37	10.13	2.98	8.66	10.31	7.53
	4.53 (8.15)	1.01	4.43	11.91	15.53				
	4.92 (8.86)	3.25	9.85	15.68	17.66				

Table 4-16 c. CTE 3 Interaction Effects

Variables		ST Level	JS Level	5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST	JS	14	12	0	0	0	0	0	0.017	0.167	0.533
			15	0	0	0	0				
			20	0	0.0167	0.167	0.53				
		9	12	0	0	0.05	0.15	9	30.65	64.18	81.6
			15	0.0667	0.2833	1.45	4.2				
			20	9	30.65	64.23	81.8				

Table 4-17 a. CTE 4 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	2062.673611	2062.673611	1585.99	<.0001
JS	2	4113.251667	2056.625833	1581.34	<.0001
SW	1	134.946944	134.946944	103.76	<.0001
CTE	2	361.931667	180.965833	139.15	<.0001
ST*JS	2	4107.207222	2053.603611	1579.02	<.0001
ST*SW	1	134.173611	134.173611	103.17	<.0001
ST*CTE	2	360.383889	180.191944	138.55	<.0001
JS*SW	2	265.273889	132.636944	101.98	<.0001
JS*CTE	4	721.541667	180.385417	138.7	<.0001
SW*CTE	2	2.603889	1.301944	1	0.4215
ST*JS*SW	2	263.740556	131.870278	101.4	<.0001
ST*JS*CTE	4	718.452778	179.613194	138.1	<.0001
JS*SW*CTE	4	5.202778	1.300694	1	0.4752

Table 4-17 b. CTE 4 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0	0	0	0.01	0.87	3.12	9.22	15.14
	9	0.87	3.12	9.22	15.14				
Joint Spacing (ft)	12	0	0	0	0	1.31	4.68	13.83	22.69
	15	0	0	0.01	0.03				
	20	1.31	4.68	13.83	22.69				
Slab Width (ft)	14	0.22	0.89	3.07	5.64	0.43	1.34	3.08	3.87
	12	0.65	2.23	6.15	9.51				
CTE, με/˚F (με/˚C)	5.42 (9.76)	0.12	0.45	1.73	3.68	0.73	2.5	6.12	7.77
	5.75 (10.35)	0.34	1.28	4.27	7.59				
	6.07 (10.93)	0.85	2.95	7.84	11.45				

Table 4-17 c. CTE 4 Interaction Effects

Variables		ST, CTE Level	JS, SW, ST Level	5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST	JS	14	12	0	0	0	0	0	0	0	0.017
			15	0	0	0	0				
			20	0	0	0	0.02				
		9	12	0	0	0	0	2.62	9.35	27.65	45.37
			15	0	0	0.02	0.07				
			20	2.62	9.35	27.65	45.4				
ST	SW	14	12	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
			14	0.00	0.00	0.00	0.00				
		9	12	1.30	4.46	12.30	19.01	0.86	2.68	6.16	7.73
			14	0.44	1.78	6.14	11.28				
CTE	ST	5.42 (9.76)	14	0	0	0	0	0.23	0.9	3.45	7.37
			9	0.23	0.9	3.45	7.37				
		5.75 (10.35)	14	0	0	0	0	0.68	2.55	8.53	15.18
			9	0.68	2.55	8.53	15.2				
		6.07 (10.93)	14	0	0	0	0.02	1.7	5.9	15.68	22.87
			9	1.7	5.9	15.68	22.9				
CTE	JS	5.42 (9.76)	12	0.00	0.00	0.00	0.00	0.35	1.35	5.18	11.03
			15	0.00	0.00	0.00	0.03				
			20	0.35	1.35	5.18	11.03				
		5.75 (10.35)	12	0.00	0.00	0.00	0.00	1.03	3.83	12.80	22.75
			15	0.00	0.00	0.00	0.03				
			20	1.03	3.83	12.80	22.75				
		6.07 (10.93)	12	0.00	0.00	0.00	0.00	2.55	8.85	23.50	34.30
			15	0.00	0.00	0.03	0.05				
			20	2.55	8.85	23.50	34.30				

Table 4-18 a. CTE 5 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	9847.25444	9847.25444	985.05	<.0001
JS	2	24329.07056	12164.53528	1216.86	<.0001
SW	1	202.58778	202.58778	20.27	0.0041
CTE	2	476.70889	238.35444	23.84	0.0014
ST*JS	2	10674.45056	5337.22528	533.9	<.0001
ST*SW	1	24.66778	24.66778	2.47	0.1673
ST*CTE	2	4.62889	2.31444	0.23	0.8001
JS*SW	2	115.03389	57.51694	5.75	0.0403
JS*CTE	4	237.76111	59.44028	5.95	0.0278
SW*CTE	2	35.24222	17.62111	1.76	0.2499
ST*JS*SW	2	275.34722	137.67361	13.77	0.0057
ST*JS*CTE	4	667.98111	166.99528	16.71	0.0021
JS*SW*CTE	4	18.39111	4.59778	0.46	0.7639

Table 4-18 b. CTE 5 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0.43	1.29	3.59	6.3	28.85	31.89	32.87	33.08
	9	29.28	33.18	36.46	39.38				
Joint Spacing (ft)	12	0.01	0.03	0.1	0.18	43.98	49.86	54.76	59.06
	15	0.58	1.78	5.12	9.09				
	20	43.98	49.89	54.86	59.24				
Slab Width (ft)	14	13.77	16.34	18.47	20.47	2.18	1.79	3.11	4.74
	12	15.95	18.13	21.58	25.21				
CTE, με/˚F (με/˚C)	5.63 (10.13)	12.83	15.76	17.46	18.77	3.78	3.05	5.63	8.83
	5.96 (10.73)	15.13	17.14	19.53	22.15				
	6.30 (11.34)	16.61	18.81	23.09	27.6				

Table 4-18 c. CTE 5 Interaction Effects

Variables			ST, CTE, JS Level		JS, SW, JS Level		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST	JS		14		12		0	0	0	0	1.3	3.867	10.77	18.9
					15		0	0	0	0				
					20		1.3	3.87	10.77	18.9				
			9		12		0.017	0.067	0.2	0.37	86.65	95.85	98.75	99.22
					15		1.17	3.57	10.23	18.2				
					20		86.67	95.92	98.95	99.6				
CTE	JS		5.63 (10.13)		12		0.00	0.03	0.03	0.08	38.30	46.58	50.35	52.30
					15		0.20	0.65	1.98	3.85				
					20		38.30	46.60	50.38	52.38				
			5.96 (10.73)		12		0.00	0.03	0.10	0.15	44.90	49.90	53.95	57.93
					15		0.50	1.48	4.43	8.23				
					20		44.90	49.93	54.05	58.08				
			6.30 (11.34)		12		0.03	0.05	0.18	0.33	48.73	53.10	59.98	66.95
					15		1.05	3.23	8.95	15.20				
					20		48.75	53.15	60.15	67.28				
ST	JS	SW	14	12	12		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					14		0.00	0.00	0.00	0.00				
				15	12		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					14		0.00	0.00	0.00	0.00				
				20	12		1.70	5.03	13.77	23.53	0.80	2.33	6.00	9.27
					14		0.90	2.70	7.77	14.27				
			9	12	12		0.03	0.13	0.33	0.63	0.03	0.13	0.27	0.53
					14		0.00	0.00	0.07	0.10				
				15	12		1.87	5.60	15.73	27.20	1.40	4.07	11.00	18.03
					14		0.47	1.53	4.73	9.17				
				20	12		92.10	98.03	99.63	99.90	10.87	4.23	1.37	0.63
					14		81.23	93.80	98.27	99.27				
CTE	ST	JS	5.63 (10.13)		14	12	0	0	0	0	0.3	1	2.85	5.6
						15	0	0	0	0				
						20	0.3	1	2.85	5.6				
					9	12	0	0.05	0.05	0.15	76.3	92.15	97.85	99
						15	0.4	1.3	3.95	7.7				
						20	76.3	92.2	97.9	99.15				
			5.96 (10.73)		14	12	0	0	0	0	1	3	8.85	16.45
						15	0	0	0	0				
						20	1	3	8.85	16.45				
					9	12	0	0.05	0.2	0.3	88.8	96.8	99.05	99.4
						15	1	2.95	8.85	16.45				
						20	88.8	96.85	99.25	99.7				
			6.30 (11.34)		14	12	0	0	0	0	2.6	7.6	20.6	34.65
						15	0	0	0	0				
						20	2.6	7.6	20.6	34.65				
					9	12	0.05	0.1	0.35	0.65	94.85	98.6	99.35	99.25
						15	2.1	6.45	17.9	30.4				
						20	94.9	98.7	99.7	99.9				

Table 4-19 a. CTE 6 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	10441.43361	10441.43361	612.65	<.0001
JS	2	26380.04056	13190.02028	773.92	<.0001
SW	1	294.1225	294.1225	17.26	0.006
CTE	2	1833.67056	916.83528	53.8	0.0001
ST*JS	2	7658.53389	3829.26694	224.68	<.0001
ST*SW	1	55.00694	55.00694	3.23	0.1225
ST*CTE	2	6.22056	3.11028	0.18	0.8376
JS*SW	2	173.015	86.5075	5.08	0.0513
JS*CTE	4	841.24444	210.31111	12.34	0.0047
SW*CTE	2	59.735	29.8675	1.75	0.2515
ST*JS*SW	2	393.63722	196.81861	11.55	0.0088
ST*JS*CTE	4	2562.82444	640.70611	37.59	0.0002
JS*SW*CTE	4	29.92	7.48	0.44	0.7775

Table 4-19 b. CTE 6 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0.02	0.09	0.53	1.67	15.11	27.27	32.82	34.54
	9	15.12	27.36	33.35	36.22				
Joint Spacing (ft)	12	0	0	0.03	0.09	22.67	40.93	49.32	52.07
	15	0.04	0.23	1.46	4.58				
	20	22.67	40.93	49.34	52.16				
Slab Width (ft)	14	5.71	12.49	16.27	17.68	3.72	2.47	1.35	2.53
	12	9.43	14.96	17.62	20.21				
CTE, με/˚F (με/˚C)	5.19 (9.34)	5.02	11.91	16.18	17.63	4.43	3.03	1.33	2.4
	5.46 (9.83)	8.24	14.32	17.13	19.18				
	5.56 (10.01)	9.45	14.94	17.52	20.03				

Table 4-19 c. CTE 6 Interaction Effects

Variables		ST, CTE Level	JS Level	5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST	JS	14	12	0	0	0	0	0.05	0.267	1.6	5.017
			15	0	0	0	0				
			20	0.05	0.2667	1.6	5.02				
		9	12	0	0	0.05	0.18	45.28	81.6	97.03	99.12
			15	0.0833	0.4667	2.917	9.17				
			20	45.283	81.6	97.08	99.3				

Table 4-20 a. CTE 7 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	P Value
ST	1	3379.484444	3379.484444	4419.23	<.0001
JS	2	6751.226667	3375.613333	4414.17	<.0001
SW	1	148.84	148.84	194.63	<.0001
CTE	2	159.171667	79.585833	104.07	<.0001
ST*JS	2	6735.742222	3367.871111	4404.05	<.0001
ST*SW	1	148.84	148.84	194.63	<.0001
ST*CTE	2	158.110556	79.055278	103.38	<.0001
JS*SW	2	292.826667	146.413333	191.46	<.0001
JS*CTE	4	316.856667	79.214167	103.59	<.0001
SW*CTE	2	1.635	0.8175	1.07	0.4008
ST*JS*SW	2	292.826667	146.413333	191.46	<.0001
ST*JS*CTE	4	314.737778	78.684444	102.89	<.0001
JS*SW*CTE	4	3.453333	0.863333	1.13	0.425

Table 4-20 b. CTE 7 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0	0	0	0.01	1.19	4.36	12.49	19.38
	9	1.19	4.36	12.49	19.39				
Joint Spacing (ft)	12	0	0	0	0	1.78	6.54	18.72	29.07
	15	0	0	0.02	0.03				
	20	1.78	6.54	18.72	29.07				
Slab Width (ft)	14	0.32	1.28	4.37	7.67	0.56	1.79	3.76	4.07
	12	0.87	3.08	8.12	11.73				
CTE, με/˚F (με/˚C)	5.72 (10.30)	0.28	1.09	3.84	7.04	0.69	2.32	4.85	5.14
	5.94 (10.69)	0.54	2.04	6.2	9.88				
	6.15 (11.07)	0.97	3.41	8.69	12.18				

Table 4-20 c. CTE 7 Interaction Effects

Variables		ST, CTE Level	JS, ST Level	5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST	JS	14	12	0	0	0	0	0	0	0	0.033
			15	0	0	0	0				
			20	0	0	0	0.03				
		9	12	0	0	0	0	3.567	13.08	37.43	58.1
			15	0	0	0.033	0.07				
			20	3.5667	13.083	37.43	58.1				
CTE	ST	5.72 (10.30)	14	0	0	0	0	0.55	2.183	7.683	14.08
			9	0.55	2.1833	7.683	14.1				
		5.94 (10.69)	14	0	0	0	0.02	1.083	4.083	12.4	19.72
			9	1.0833	4.0833	12.4	19.7				
		6.15 (11.07)	14	0	0	0	0.02	1.933	6.817	17.38	24.33
			9	1.9333	6.8167	17.38	24.4				

Table 4-21 a. CTE 8 ANOVA Results

Source	DF	Anova SS	Mean Square	F Value	Pr > F
ST	1	10380.21361	10380.21361	1018.33	<.0001
JS	2	22449.10722	11224.55361	1101.17	<.0001
SW	1	191.8225	191.8225	18.82	0.0049
CTE	2	345.02389	172.51194	16.92	0.0034
ST*JS	2	12149.94056	6074.97028	595.97	<.0001
ST*SW	1	38.23361	38.23361	3.75	0.1009
ST*CTE	2	1.17056	0.58528	0.06	0.9447
JS*SW	2	116.81167	58.40583	5.73	0.0406
JS*CTE	4	166.54611	41.63653	4.08	0.0619
SW*CTE	2	30.61167	15.30583	1.5	0.296
ST*JS*SW	2	244.33389	122.16694	11.98	0.008
ST*JS*CTE	4	442.73278	110.68319	10.86	0.0065
JS*SW*CTE	4	18.56167	4.64042	0.46	0.7669

Table 4-21 b. CTE 8 Main Effects

Variable▼	Level	Mean Percent Slabs Cracked				Maximum Mean Differences			
		5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
Slab Thickness (in)	14	0.07	0.32	1.77	4.72	18.14	28.27	32.79	33.96
	9	18.21	28.59	34.56	38.68				
Joint Spacing (ft)	12	0	0.02	0.07	0.21	27.28	42.74	51.21	56.51
	15	0.13	0.59	3.14	8.18				
	20	27.28	42.76	51.28	56.72				
Slab Width (ft)	14	7.25	13.17	16.93	19.39	3.77	2.57	2.46	4.62
	12	11.02	15.74	19.39	24.01				
CTE, με/˚F (με/˚C)	5.46 (9.83)	5.1	11.77	16.23	18.02	7.37	4.66	3.88	7.58
	5.87 (10.57)	9.84	15.18	18.16	21.5				
	6.13 (11.03)	12.47	16.43	20.1	25.59				

Table 4-21 c. CTE 8 Interaction Effects

Variables			ST, JS, CTE Level		JS, SW, ST Level	5 yr	10 yr	20 yr	30 yr	$\Delta_{MAX\ 5}$	$\Delta_{MAX\ 10}$	$\Delta_{MAX\ 20}$	$\Delta_{MAX\ 30}$
ST	JS		14		12	0	0	0	0	0.2	0.967	5.3	14.17
					15	0	0	0	0				
					20	0.2	0.97	5.3	14.2				
			9		12	0	0.03	0.13	0.42	54.37	84.52	97.12	98.85
					15	0.25	1.18	6.28	16.4				
					20	54.37	84.55	97.25	99.3				
ST	JS	SW	14	12	12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					14	0.00	0.00	0.00	0.00				
				15	12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					14	0.00	0.00	0.00	0.00				
				20	12	0.27	1.30	6.97	18.00	0.13	0.67	3.33	7.67
					14	0.13	0.63	3.63	10.33				
			9	12	12	0.00	0.07	0.23	0.73	0.00	0.07	0.20	0.63
					14	0.00	0.00	0.03	0.10				
				15	12	0.43	1.93	10.13	25.50	0.37	1.50	7.70	18.27
					14	0.07	0.43	2.43	7.23				
				20	12	65.43	91.13	99.00	99.83	22.13	13.17	3.50	1.13
					14	43.30	77.97	95.50	98.70				
CTE	ST	JS	5.63 (10.13)	14	12	0.00	0.00	0.00	0.00	0.05	0.15	1.00	3.10
					15	0.00	0.00	0.00	0.00				
					20	0.05	0.15	1.00	3.10				
				9	12	0.00	0.00	0.05	0.15	30.45	70.05	94.05	98.20
					15	0.10	0.40	2.20	6.50				
					20	30.45	70.05	94.10	98.35				
			5.96 (10.73)	14	12	0.00	0.00	0.00	0.00	0.15	0.80	4.50	12.90
					15	0.00	0.00	0.00	0.00				
					20	0.15	0.80	4.50	12.90				
				9	12	0.00	0.05	0.10	0.40	58.65	89.05	98.30	99.20
					15	0.25	1.10	5.95	16.10				
					20	58.65	89.10	98.40	99.60				
			6.30 (11.34)	14	12	0.00	0.00	0.00	0.00	0.40	1.95	10.40	26.50
					15	0.00	0.00	0.00	0.00				
					20	0.40	1.95	10.40	26.50				
				9	12	0.00	0.05	0.25	0.70	74.00	94.45	99.00	99.15
					15	0.40	2.05	10.70	26.50				
					20	74.00	94.50	99.25	99.85				

CHAPTER 5: CONCLUSIONS

5.1 Introduction

In this chapter a summary of research conducted in this project is presented followed by findings and conclusions regarding CTE measurement and factors affecting it. Long term effects of CTE on the performance of jointed concrete pavements are also presented. Recommendations about CTE testing procedure are also presented in this chapter.

5.2 Summary of Work Performed

This report documents the effect of eight different coarse aggregate sources on the CTE of a typical MDOT concrete paving mixture. Over 700 concrete specimens were fabricated for various tests. At least three replicate specimens were fabricated for each test for a given test date. The test variables included in the laboratory investigation included the aggregate geology, the age of the sample at the time of testing, and the number of heating-cooling cycles applied to the sample. The details about the experimental program and the test method are documented in chapter 3. The results from the laboratory investigation and the impact of the test variables on the magnitude of CTE are documented in chapter 4 of the report.

The impact of CTE on the structural design and performance of jointed concrete pavements was also investigated as part of this research study and the results are presented in chapter 4.

5.3 Factors Affecting Measurement of CTE

The following conclusions were based on the laboratory investigation and the statistical analyses of the dataset;

- The magnitude of the measured CTE varied with aggregate geology. The measured CTE magnitudes for the various aggregate geologies compared favorably with the published values.
- Statistical analysis showed:

    1) Magnitude of the measured CTE is significantly (statistically) influenced by the age of the sample at the time of testing.

    2) Magnitude of the measured CTE at the early ages (3, 7, 14, 28 days) were significantly (statistically) different than the magnitudes determined at the end of 90, 180, and 365 days.

    3) Operationally, the impact of this difference on transverse cracking (as computed by the M-E PDG software for 14, 28, and 90 days) was not found to be significant.

- The number of heating-cooling cycles in CTE test affects the magnitude of CTE. The CTE value calculated based on the first cycle was higher than the values calculated based on second and third cycles. Statistically the CTE values based on second and third cycles were not different from each other.
- Coefficient of variance for the data set ranged from 2-6%. Approximately 94% of the data set has a δ_{CTE} between ± 0.17 $\mu\varepsilon/^{o}F$ (0.3 $\mu\varepsilon/^{o}C$). It was observed that, generally, concrete with higher CTE values is more sensitive to variability compared to concrete with low CTE values.

5.4 Impact of CTE on Long Term Pavement Performance

M-E PDG software along with statistical analyses were used to investigate the impact of CTE value and its interaction with other design factors on long term performance of jointed concrete pavements in cracking.

It was found that the impact of CTE, slab thickness, and joint spacing on transverse cracking were statistically significant. Practical significance was evaluated by comparing the results of the analyses with published criteria on percent slabs cracked. The selected practical significance criteria states that if a rigid pavement shows 7.5% slabs cracked after 30 years, it's a good-normal slab. If it shows 15% slabs cracked, it's a normal-poor slab.

It was observed that, thinner slab, longer joint spacing, and higher CTE values resulted in increased percent of slabs cracked over the age of a pavement.

Based on the results from a number of analyses, it was observed that when comparing the effect of CTE combined with the effect of slab thickness or joint spacing, the combined effect of CTE and joint spacing is more significant than the effect of CTE and slab thickness.

5.5 Suggested Recommendations

The following recommendations are suggested:

- The CTE value based on one cycle is probably not reliable. It is suggested that the test specimen should be subjected to three test cycles of heating and cooling. The test data from cycles two or three should be used for the computation of CTE.
- Based on the operational significance analysis it is suggested that CTE measured at the end of 28 days can used as an input for jointed concrete pavement design.
- Automation of the temperature and displacement readings with a rate of one reading per minute (as recommended by Texas DOT test method 428-A) makes the testing process and CTE determination more reliable.

5.6. Recommended CTE Values

The following table lists the CTE values for each coarse aggregate tested, based on the recommendations above:

Table 5-1. Recommended CTE Values for Concrete Made with Different Coarse Aggregate

Mix ID	Primary Aggregate Class	Pit Number	28-Day CTE (με/°F)		28-Day CTE (με/°C)	
			Cycle #2	Cycle #3	Cycle #2	Cycle #3
CTE 1	Limestone	71-47	4.54	4.55	8.17	8.18
CTE 2	Gravel	19-56	5.84	5.84	10.51	10.52
CTE 3	Dolomitic Limestone	75-05	4.51	4.47	8.12	8.04
CTE 4	Slag	82-19	5.69	5.73	10.24	10.31
CTE 5	Dolomite	49-65	5.91	5.91	10.65	10.64
CTE 6	Gabbro (Trap Rock)	95-10	5.40	5.38	9.72	9.68
CTE 7	Dolomite	58-11	5.93	5.77	10.67	10.38
CTE 8	Dolomite	91-06	5.90	5.87	10.63	10.57

CHAPTER 6: REFERENCES

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APPENDIX A: SUMMARY OF DOT SURVEY

Table A-1. Summary of DOT Survey

Questions	Alabama DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	No. ALDOT has initiated a research project with Auburn University to test the CTE of concrete mixtures typically used in the state. Tests are being performed in accordance with AASHTO TP 60.
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"	This information is currently not being used.
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): *ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*.	ALDOT mostly uses the following aggregates: siliceous river gravel, quartzite, high-calcium limestone, dolomitic limestone, granite, and sandstone.
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?	The only results available at this stage are for concrete made with river gravel: CTE = 12.5 x 10-6 in./in./°C.
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?	Coarse agg type and amount, fine agg type and amount, relative humidity, concrete age, and w/cm.
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	No. The research project with Auburn University is currently active and results will be made available when the research has been completed.

Table A-1. Summary of DOT Survey, continued

Questions	Alaska DOT	Colorado DOT	Kentucky DOT	Maine DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	No	No	No	Maine DOT does not currently utilize concrete pavement in our Highway Program.
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"			N/A	
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): ***ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*****.**			Sedimentary rocks including limestones, dolomites and gravels.	
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?			N/A	
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?			N/A	
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?			No	

Table A-1. Summary of DOT Survey, continued

Questions	Minnesota DOT	NebraskaDOT	New Hampshire DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	No	No	We do not use concrete paving in NH
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"	Aggregate type does not affect design	N/A	
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): *ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*.	Typically: Limestone (including dolomites), gravels, granite, gneiss	Limestone	
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?	Do not have values other than assumed values that are listed in literature	N/A	
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?	No experience. Certainly ASR could result in expansion of beam specimens. The mix design including cement replacements would certainly affect results.	N/A	
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	We are more concerned about thermal expansion in bridges than pavements. We have not experienced cracking problems that we can attribute to aggregate type.	N/A	

Table A-1. Summary of DOT Survey, continued

Questions	North Carolina DOT	Oregon DOT	Pennsylvania DOT	South Dakota DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	No	No	No	No
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"		No don't use in current design process – spacing based on research	N/A	ME Pavement Design Guide Input
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): *ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*.	Predominantly granite and similar volcanics.	Limestone, dolomite, gravels	We have many types of coarse aggregates in the state. Their inclusion in concrete paving mix designs is based on quality test parameters. i.e. – sodium sulfate, amount of deleterious material, etc.	Limestone, Granite, Quartzite.
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?		N/A	N/A	3.8 x 10^{-6} / °F (Limestone) 4.6 x 10-6 / °F (Granite) 6.8 x 10-6 / °F (Quartzite)
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?		N/A	N/A	Unknown.
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	None available.	Go to Datapave.com SHRP site.	N/A	No.

Table A-1. Summary of DOT Survey, continued

Questions	Texas DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	We are conducting CTE tests for all the aggregate sources used in concrete. The Test protocol is Tex-428-A, Determining the Coefficient of Thermal Expansion of Concrete. Link to TXDOT web. http://manuals.dot.state.tx.us/dynaweb/colmates/cnn/@Generic__BookView;cs=default;ts=default
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"	CTE has not been used for pavement design or aggregate acceptance. However, some concrete pavement projects have required CTE Range.
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): *ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*.	Limestone and river gravel are typical; however, dolomite and granite sources are also used.
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?	From 90 CTE values, the mean value is 5.2 x 10-6/F with a median of 4.9 x 10-6/F. The CTE values range from 4.0 to 6.8 x 10-6/F, with 4.4 x 10-6/F as the most frequent value.
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?	We have conducted CTE tests for varying types of cement, cement/flyash, and multiple sources of fine aggregates, only the coarse aggregates have made a significant impact on the test results.
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	At this time, the research results are for internal use only.

Table A-1. Summary of DOT Survey, continued

Questions	Utah DOT	Virginia DOT	Washington DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	No, but we just completed construction of our apparatus.	No	No
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"	Looking at pavement design input primarily, possibly for forensic review of distressed pavements		Not yet, however with the 20XX design procedure we will.
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): *ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*.	Majority is granite, with some dolomitic limestone in the north. Southern Utah is sandstones.		We have a wide variety of lithologies in this state including glacial outwash gravels; volcanic rocks such as andesite and basalt; as well as granites and metamorhphics.
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?	Currently undermined.		We have not specifically tested our aggregates. Typical values for the sources listed above are used.
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?	Discussions with others have indicated that the sand component can have impact.		Unknown
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	Not at this time.		None

Table A-1. Summary of DOT Survey, continued

Questions	West Virginia DOT
Do you conduct CTE tests for your typical concrete paving mixtures? If yes, what test protocol does your agency follow?	No.
How do you utilize your CTE information (for example, as an input into pavement design, aggregate acceptance, etc.)?"	N/A
What are the typical lithologies of the coarse aggregate used in concrete paving mixtures on state/federal funded projects? Example lithologies are (but not limited to): ***ultramafic, granite, schist, gneiss, limestone, dolomite, sandstone, slate, etc*****.**	Limestone, sandstone, and river gravel
What are the typical CTE ranges for concrete mixtures containing the various coarse aggregate lithologies stated in the previous question?	We don’t conduct (or require) CTE tests on our concrete mixtures.
In your experience with CTE testing, what other components of the concrete mix (fine aggregate, cement, cement replacements,etc) have a significant impact on the test results?	We haven’t conducted any CTE tests.
Do you have any research results, either published or unpublished, that you could send or provide the location on your website?	No.

APPENDIX B: HARDENED CONCRETE PROPERTIES TABLES

Table B-1. Hardened Concrete Properties Table for CTE 1

CTE 1	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2289	3907	4918	5211	5416	6622	6476
Sample#2	2490	4033	4980	4093	5125	6241	6734
Sample#3	2869	4223	3958	5227	4847	6162	6320
Average	2549	4054	4619	4844	5129	6342	6510
Elastic Modulus (psi)							
Sample#1	2720277	3845841	4384180	4246291	4565108	5044775	4876878
Sample#2	1599140	3570805	4250277	4083412	4303844	4960549	5024210
Sample#3	3219544	3969268	4095948	4458081	4598727	5005437	5155223
Average	2512987	3795305	4243468	4262595	4489226	5003587	5018770
Split Tensile Strength (psi)							
Sample#1	256	433	491	500	482	596	634
Sample#2	241	434	445	440	581	569	666
Sample#3	254	437	479	570	485	611	602
Average	248	435	472	503	516	592	634
Flexural Strength (psi)							
Sample#1	469	745	675	747	818	793	827
Sample#2	454	822	674	913	850	841	845
Sample#3	543	679	699	763	836	840	841
Average	499	748	683	808	835	825	838

Table B-2. Hardened Concrete Properties Table for CTE 2

CTE 2	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2051	3909	3685	4148	5292	5818	5814
Sample#2	2223	3770	3940	4388	4779	5584	5887
Sample#3	2098	3599	3745	3630	4824	5179	4631
Average	2124	3759	3790	4055	4965	5527	5444
Elastic Modulus (psi)							
Sample#1	3504811	3894648	4165865	4436156	4746978	4693725	5765917
Sample#2	3377411	4226295	4272793	4740568	4884807	5134287	5177605
Sample#3	2944210	4134072	4352554	4557317	5038801	5082407	5594764
Average	3275477	4085005	4263737	4578014	4890195	4970139	5512762
Split Tensile Strength (psi)							
Sample#1	258	389	412	446	502	512	568
Sample#2	283	444	445	461	534	493	594
Sample#3	250	417	428	466	471	519	629
Average	264	417	428	458	502	508	597
Flexural Strength (psi)							
Sample#1	396	502	614	676	695	890	827
Sample#2	454	504	630	655	691	694	845
Sample#3	429	484	709	475	691	751	841
Average	426	497	651	602	692	778	838

Table B-3. Hardened Concrete Properties Table for CTE 3

CTE 3	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2097	3283	3171	3767	4097	4707	5310
Sample#2	2131	2889	3377	3736	3695	4780	5601
Sample#3	2246	3159	3459	3701	4109	5183	5852
Average	2158	3110	3336	3735	3967	4890	5588
Elastic Modulus (psi)							
Sample#1	3007745	3825496	4247803	3988223	4474795	5143779	5260887
Sample#2	3307029	3902588	4161331	4148092	4603508	4769219	4987492
Sample#3	3060070	3793156	4091292	4388647	4626630	4866031	5256010
Average	3124948	3840414	4166808	4174987	4568311	4926343	5168130
Split Tensile Strength (psi)							
Sample#1	295	367	415	414	502	482	488
Sample#2	236	382	451	456	489	505	536
Sample#3	263	332	436	452	477	514	588
Average	265	360	434	440	489	501	537
Flexural Strength (psi)							
Sample#1	414	543	673	670	658	783	758
Sample#2	414	585	626	677	666	792	962
Sample#3	479	602	620	655	612	740	787
Average	436	577	639	667	645	772	836

Table B-4. Hardened Concrete Properties Table for CTE 4

CTE 4	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2430	4041	4664	4728	5056	6483	6665
Sample#2	2491	4039	4239	5226	5216	5924	7087
Sample#3	2518	3811	4345	5015	5235	6146	6578
Average	2480	3964	4416	4990	5169	6184	6777
Elastic Modulus (psi)							
Sample#1	3446678	4467453	4252860	4525155	4549298	4870545	5288507
Sample#2	3487046	4230876	4345819	4567307	4729983	5078483	5037622
Sample#3	3532711	4211250	4541989	3823767	4694448	4973960	5246620
Average	3488812	4303193	4380223	4546231	4639640	4974330	5190916
Split Tensile Strength (psi)							
Sample#1	297	401	475	510	509	518	627
Sample#2	334	365	405	524	518	584	655
Sample#3	323	390	465	538	493	550	557
Average	318	385	449	524	507	551	613
Flexural Strength (psi)							
Sample#1	694	605	680	791	784	756	945
Sample#2	715	594	689	767	881	882	878
Sample#3	520	618	692	717	827	774	842
Average	643	605	687	758	831	804	888

Table B-5. Hardened Concrete Properties Table for CTE 5

CTE 5	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2308	2800	3337	3760	4165	5015	5776
Sample#2	2281	3167	3205	4030	3849	4940	5816
Sample#3	2240	3138	3271	4019	4089	4863	5708
Average	2276	3035	3271	3936	4035	4939	5767
Elastic Modulus (psi)							
Sample#1	2770536	3319209	3694044	4181223	4773375	5431180	6054583
Sample#2	2738093	3551937	3531425	4203011	4462819	5033959	6054626
Sample#3	2485543	3182731	3816278	4430976	4720948	5243949	5784749
Average	2664724	3351292	3680582	4271736	4652381	5236363	5964653
Split Tensile Strength (psi)							
Sample#1	261	395	490	482	509	469	558
Sample#2	256	394	464	472	500	525	565
Sample#3	254	383	489	530	524	475	533
Average	257	391	481	494	511	490	552
Flexural Strength (psi)							
Sample#1	415	556	543	638	727	667	947
Sample#2	427	462	612	662	727	715	923
Sample#3	404	529	701	728	740	713	879
Average	415	516	619	676	731	699	916

Table B-6. Hardened Concrete Properties Table for CTE 6

CTE 6	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2314	3297	3716	4778	5322	4950	5572
Sample#2	2335	3540	3914	4802	5437	5190	5235
Sample#3	2315	3469	4077	4164	4616	4962	6019
Average	2321	3435	3902	4581	5125	5034	5609
Elastic Modulus (psi)							
Sample#1	3509646	4603350	5113319	5474624	5486636	5319340	5750771
Sample#2	4180986	4603342	4791762	5326848	5496331	6061649	6044256
Sample#3	4142140	4875414	5204367	4995331	5183808	5224772	6570346
Average	3944258	4694035	5036483	5265601	5388925	5535254	6121791
Split Tensile Strength (psi)							
Sample#1	318	386	342	391	484	520	566
Sample#2	300	401	392	452	515	546	604
Sample#3	318	314	467	518	499	512	579
Average	312	367	400	454	500	526	583
Flexural Strength (psi)							
Sample#1	437	521	712	682	738	763	924
Sample#2	481	541	614	715	746	788	842
Sample#3	487	492	573	892	710	798	864
Average	468	518	633	763	731	783	877

Table B-7. Hardened Concrete Properties Table for CTE 7

CTE 7	Age (Days)						
	1	3	7	14	28	90	365
Compressive Strength (psi)							
Sample#1	2389	3752	4685	4587	6032	6242	6772
Sample#2	2359	3757	4442	4811	5531	6357	7122
Sample#3	2380	4107	4168	4418	5913	6455	7344
Average	2376	3872	4432	4605	5825	6352	7079
Elastic Modulus (psi)							
Sample#1	2727454	3101702	3865715	4290294	4564800	4603709	5020650
Sample#2	2583834	3367417	4060420	4186334	4512137	4796854	5143097
Sample#3	2531341	3405353	3873462	4069158	4367202	4681462	4984448
Average	2614210	3291491	3933199	4181929	4481379	4694008	5049398
Split Tensile Strength (psi)							
Sample#1	282	407	476	559	587	604	675
Sample#2	293	456	430	464	538	662	693
Sample#3	282	436	453	473	557	611	698
Average	286	433	453	499	561	626	689
Flexural Strength (psi)							
Sample#1	423	577	735	784	804	802	916
Sample#2	463	519	642	801	887	783	988
Sample#3	482	599	662	775	770	820	892
Average	456	565	680	787	820	802	932

Table B-8. Hardened Concrete Properties Table for CTE 8

CTE 8	Age (Days)				
	7	14	28	90	365
Compressive Strength (psi)					
Sample#1	3785	4234	4811	5839	6451
Sample#2	3643	4442	5094	6032	6635
Average	3714	4338	4953	5936	6543
Elastic Modulus (psi)					
Sample#1	3930757	4119392	4758942	5249832	5526363
Sample#2	4170204	4187470	4663753	5137098	5661545
Average	4050480	4153431	4711347	5193465	5593954
Split Tensile Strength (psi)					
Sample#1	380	435	489	478	632

APPENDIX C: COEFFICIENT OF THERMAL EXPANSION TABLES

Table C-1. CTE Values for CTE 1

CTE 1, με/^{o}F (με/^{o}C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	4.56 (8.21)	4.54 (8.17)	4.43 (7.98)	4.57 (8.23)	4.81 (8.66)	4.99 (8.98)	5.02 (9.03)
Sample#2	4.63 (8.34)	4.52 (8.14)	4.52 (8.13)	4.64 (8.35)	4.59 (8.27)	4.98 (8.97)	5.12 (9.21)
Sample#3	4.43 (7.97)	4.47 (8.05)	4.60 (8.28)	4.42 (7.96)	4.74 (8.53)	5.08 (9.15)	4.78 (8.60)
Average	4.54 (8.17)	4.51 (8.12)	4.52 (8.13)	4.54 (8.18)	4.77 (8.59)	5.02 (9.03)	4.97 (8.95)
Tx 428-A							
Sample#1	4.54 (8.17)	4.62 (8.31)	4.54 (8.17)	4.53 (8.15)	4.92 (8.86)	5.08 (9.15)	5.09 (9.16)
Sample#2	4.70 (8.46)	4.51 (8.12)	4.64 (8.36)	4.61 (8.30)	4.61 (8.30)	5.01 (9.03)	5.07 (9.13)
Sample#3	4.56 (8.21)	4.63 (8.33)	4.56 (8.21)	4.41 (7.93)	4.70 (8.46)	5.15 (9.27)	4.87 (8.77)
Average	4.60 (8.28)	4.59 (8.25)	4.58 (8.25)	4.51 (8.12)	4.81 (8.66)	5.08 (9.15)	5.01 (9.02)

Table C-2. CTE Values for CTE 2

CTE 2, με/^{o}F (με/^{o}C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	5.90 (10.63)	5.86 (10.54)	5.85 (10.53)	5.88 (10.58)	6.06 (10.91)	6.22 (11.19)	6.11 (10.99)
Sample#2	5.62 (10.12)	5.74 (10.34)	5.95 (10.71)	5.86 (10.55)	5.78 (10.40)	6.42 (11.55)	6.32 (11.38)
Sample#3	5.56 (10.01)	5.29 (9.52)	5.82 (10.47)	5.79 (10.43)	6.04 (10.87)	6.11 (11.01)	5.92 (10.65)
Average	5.70 (10.25)	5.63 (10.13)	5.87 (10.57)	5.85 (10.52)	5.96 (10.73)	6.25 (11.25)	6.11 (11.01)
Tx 428-A							
Sample#1	6.03 (10.85)	5.82 (10.48)	5.86 (10.55)	5.94 (10.69)	6.14 (11.05)	6.34 (11.41)	6.19 (11.15)
Sample#2	5.60 (10.07)	5.71 (10.28)	5.88 (10.58)	5.70 (10.26)	5.80 (10.44)	6.38 (11.49)	6.18 (11.13)
Sample#3	5.61 (10.09)	5.39 (9.71)	5.94 (10.69)	5.81 (10.46)	6.13 (11.03)	6.06 (10.90)	5.95 (10.72)
Average	5.74 (10.34)	5.64 (10.15)	5.89 (10.61)	5.82 (10.47)	6.02 (10.84)	6.26 (11.27)	6.11 (11.00)

Table C-3. CTE Values for CTE 3

CTE 3, με/^{o}F (με/^{o}C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	4.35 (7.83)	4.41 (7.94)	4.52 (8.14)	4.47 (8.04)	4.65 (8.37)	4.74 (8.53)	4.74 (8.54)
Sample#2	4.20 (7.57)	4.10 (7.39)	4.43 (7.98)	4.42 (7.96)	4.40 (7.91)	4.67 (8.41)	4.92 (8.86)
Sample#3	4.52 (8.14)	4.42 (7.95)	4.55 (8.18)	4.63 (8.33)	4.6 5(8.36)	4.63 (8.34)	4.64 (8.35)
Average	4.36 (7.85)	4.31 (7.76)	4.50 (8.10)	4.51 (8.11)	4.56 (8.21)	4.68 (8.43)	4.77 (8.58)
Tx 428-A							
Sample#1	4.49 (8.08)	4.38 (7.88)	4.46 (8.03)	4.56 (8.22)	4.75 (8.55)	4.81 (8.66)	4.79 (8.62)
Sample#2	4.18 (7.53)	3.95 (7.11)	4.46 (8.03)	4.35 (7.84)	4.45 (8.01)	4.66 (8.39)	4.85 (8.74)
Sample#3	4.42 (7.96)	4.52 (8.13)	4.60 (8.28)	4.68 (8.43)	4.73 (8.51)	4.70 (8.46)	4.72 (8.49)
Average	4.36 (7.86)	4.28 (7.71)	4.51 (8.11)	4.53 (8.16)	4.64 (8.35)	4.73 (8.51)	4.79 (8.62)

Table C-4. CTE Values for CTE 4

CTE 4, με/^{o}F (με/^{o}C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	5.60 (10.08)	5.72 (10.30)	5.74 (10.33)	5.75 (10.34)	5.92 (10.66)	6.04 (10.88)	6.19 (11.14)
Sample#2	5.57 (10.03)	5.43 (9.78)	5.42 (9.75)	5.55 (10.00)	6.03 (10.86)	6.03 (10.86)	6.21 (11.18)
Sample#3	5.68 (10.23)	5.66 (10.18)	5.52 (9.94)	5.81 (10.46)	6.07 (10.92)	5.95 (10.72)	5.95 (10.70)
Average	5.62 (10.11)	5.60 (10.09)	5.56 (10.01)	5.70 (10.27)	6.01 (10.81)	6.01 (10.82)	6.11 (11.01)
Tx 428-A							
Sample#1	5.53 (9.96)	5.59 (10.06)	5.67 (10.21)	5.79 (10.43)	6.02 (10.84)	6.12 (11.01)	6.28 (11.31)
Sample#2	5.54 (9.98)	5.48 (9.87)	5.44 (9.79)	5.46 (9.83)	5.98 (10.76)	5.92 (10.66)	6.15 (11.07)
Sample#3	5.85 (10.53)	5.86 (10.54)	5.42 (9.76)	5.89 (10.60)	6.21 (11.17)	5.92 (10.65)	5.88 (10.59)
Average	5.64 (10.15)	5.64 (10.16)	5.51 (9.92)	5.71 (10.29)	6.07 (10.93)	5.99 (10.78)	6.11 (10.99)

Table C-5. CTE Values for CTE 5

CTE 5, με/^{o}F (με/^{o}C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	6.02 (10.84)	5.89 (10.59)	5.93 (10.67)	5.80 (10.44)	6.03 (10.85)	6.22 (11.20)	6.29 (11.33)
Sample#2	5.75 (10.35)	5.63 (10.14)	5.77 (10.39)	5.99 (10.78)	6.12 (11.01)	6.30 (11.33)	6.39 (11.51)
Sample#3	5.92 (10.66)	5.83 (10.50)	5.88 (10.58)	5.96 (10.72)	6.17 (11.11)	6.02 (10.84)	6.09 (10.96)
Average	5.90 (10.62)	5.78 (10.41)	5.86 (10.55)	5.91 (10.65)	6.10 (10.99)	6.18 (11.12)	6.26 (11.26)
Tx 428-A							
Sample#1	6.01 (10.82)	5.82 (10.48)	5.81 (10.46)	5.88 (10.59)	6.17 (11.10)	6.33 (11.39)	6.30 (11.35)
Sample#2	5.72 (10.29)	5.70 (10.26)	5.77 (10.38)	6.04 (10.88)	6.19 (11.15)	6.25 (11.25)	6.31 (11.36)
Sample#3	6.05 (10.89)	5.85 (10.53)	5.82 (10.48)	6.05 (10.90)	6.17 (11.10)	6.19 (11.15)	6.14 (11.05)
Average	5.93 (10.67)	5.79 (10.42)	5.80 (10.44)	5.99 (10.79)	6.18 (11.12)	6.26 (11.26)	6.25 (11.25)

Table C-6. CTE Values for CTE 6

CTE 6, με/^{o}F (με/^{o}C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	5.39 (9.71)	5.47 (9.85)	5.41 (9.75)	5.35 (9.63)	5.49 (9.88)	5.56 (10.00)	5.72 (10.30)
Sample#2	5.53 (9.95)	5.47 (9.84)	5.51 (9.91)	5.49 (9.89)	5.43 (9.77)	5.48 (9.87)	5.74 (10.32)
Sample#3	5.55 (10.00)	5.48 (9.87)	5.55 (9.99)	5.36 (9.66)	5.50 (9.89)	5.19 (9.34)	5.26 (9.47)
Average	5.49 (9.89)	5.47 (9.85)	5.49 (9.89)	5.40 (9.73)	5.47 (9.85)	5.41 (9.74)	5.57 (10.03)
Tx 428-A							
Sample#1	5.29 (9.52)	5.36 (9.65)	5.31 (9.56)	5.43 (9.78)	5.50 (9.90)	5.69 (10.25)	5.72 (10.29)
Sample#2	5.48 (9.87)	5.43 (9.78)	5.47 (9.84)	5.41 (9.74)	5.34 (9.62)	5.43 (9.77)	5.71 (10.28)
Sample#3	5.51 (9.92)	5.43 (9.77)	5.46 (9.82)	5.46 (9.83)	5.53 (9.95)	5.21 (9.39)	5.37 (9.67)
Average	5.43 (9.77)	5.41 (9.73)	5.41 (9.74)	5.44 (9.79)	5.46 (9.82)	5.44 (9.80)	5.60 (10.08)

Table C-7. CTE Values for CTE 7

CTE 7, με/°F (με/°C)	Age (Days)						
	3	7	14	28	90	180	365
AASHTO TP60							
Sample#1	5.85 (10.53)	5.95 (10.71)	5.98 (10.77)	5.91 (10.63)	5.95 (10.71)	6.15 (11.07)	6.15 (11.07)
Sample#2	5.97 (10.74)	5.92 (10.66)	5.82 (10.47)	5.93 (10.67)	5.95 (10.72)	6.03 (10.85)	6.25 (11.25)
Sample#3	6.02 (10.84)	5.95 (10.71)	5.96 (10.72)	5.87 (10.57)	5.98 (10.76)	5.72 (10.30)	5.82 (10.48)
Average	5.95 (10.71)	5.94 (10.69)	5.92 (10.65)	5.90 (10.62)	5.96 (10.73)	5.97 (10.74)	6.07 (10.93)
Tx 428-A							
Sample#1	5.86 (10.54)	5.91 (10.63)	5.97 (10.74)	5.95 (10.70)	5.99 (10.78)	6.16 (11.09)	6.22 (11.20)
Sample#2	5.89 (10.60)	5.97 (10.74)	5.85 (10.52)	5.87 (10.57)	5.93 (10.67)	6.02 (10.84)	6.20 (11.17)
Sample#3	6.16 (11.09)	6.00 (10.80)	6.06 (10.91)	5.82 (10.48)	6.12 (11.01)	5.78 (10.41)	5.92 (10.66)
Average	5.97 (10.74)	5.96 (10.73)	5.96 (10.73)	5.88 (10.59)	6.01 (10.82)	5.99 (10.78)	6.12 (11.01)

Table C-8. CTE Values for CTE 8

CTE 8, με/°F (με/°C)	Age (Days)					
	7	14	28	90	180	365
AASHTO TP60						
Sample#1	5.97 (10.42)	5.71 (10.28)	5.86 (10.54)	6.02 (10.84)	6.13 (11.03)	6.37 (11.46)
Sample#2	5.58 (10.04)	5.46 (9.83)	5.87 (10.56)	6.04 (10.87)	6.13 (11.04)	6.28 (11.31)
Sample#3	5.81 (10.46)	5.81 (10.46)	5.89 (10.60)	6.00 (10.81)	6.00 (10.81)	6.10 (10.97)
Average	5.73 (10.31)	5.66 (10.19)	5.87 (10.57)	6.02 (10.84)	6.09 (10.96)	6.25 (11.25)
Tx 428-A						
Sample#1	5.89 (10.61)	5.79 (10.43)	5.98 (10.77)	6.16 (11.09)	6.26 (11.26)	6.44 (11.60)
Sample#2	5.60 (10.08)	5.45 (9.82)	5.98 (10.77)	6.05 (10.90)	6.06 (10.90)	6.23 (11.22)
Sample#3	5.89 (10.61)	5.92 (10.65)	6.03 (10.86)	6.11 (10.99)	6.09 (10.96)	6.20 (11.17)
Average	5.80 (10.43)	5.72 (10.30)	6.00 (10.80)	6.11 (10.99)	6.13 (11.04)	6.29 (11.33)